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INVESTIGATION OF ISOTHERMAL, COMPRESSIBLE FLOW ACROSS A ROTATING SEALING DAM

II - COMPUTER PROGRAM

by John Zuk, Patricia J. Smith, and Lawrence P. Ludwig

Lewis Research Center
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ABSTRACT

A computer program is presented for the analysis of compressible fluid flow across a sealing dam, such as is used in a shaft seal. The mathematical model consists of two closely spaced parallel rings, one of which is rotating. The analysis is restricted to steady, laminar, subsonic, isothermal flow. The effect of rotation on mass flow, pressure distribution, and other physical parameters is determined. The computer program is written in FORTRAN IV. The input and output variables are in English units; printout of data in the International System of units is optional.

CONTENTS

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SUMMARY

A computer program is presented for steady, laminar, subsonic, isothermal, compressible-fluid flow across a sealing dam of a radial shaft seal. Output variables include mass flow, volume flow, exit Mach number, rotational flow Reynolds number, pressure flow Reynolds number, Knudsen number, center of pressure, sealing dam force, pressure distribution, power loss, and approximate temperature rise of the gas leaking through the seal. The computer program is written in FORTRAN IV for the computer at Lewis Research Center, which is an IBM 7094II/7044 or 7040 direct couple computer under IBSYS version 13 using ALTIO. All input, output, and calculations are in English units; printout of data in the International System of units is optional. The program flow charts are presented in detail and a sample problem is given.

INTRODUCTION

In a companion paper (ref. 1), the analysis is given for the mass flow and pressure distribution for a parallel set of surfaces typical of that in the sealing dam of shaft face seals (ref. 2). The analysis is for steady, laminar, subsonic, isothermal, compressible-fluid flow with rotation of one of the sealing dam surfaces. Mass flow and pressure distribution with rotation are compared with the hydrostatic case. Reference 1 shows that rotation has significant effects when the speed is high or the radial pressure differential across the sealing dam is very small and the speed is moderate. When the sealing dam radius is much greater than the sealing dam width, which, in turn, is much greater than the film thickness, and the radial pressure flow is sufficiently large, a hydrostatic analysis is shown to be valid. Further, in the analysis presented in reference 1, the region of validity of the analysis is defined as follows:

(1) The analysis is valid until the circumferential shear flow causes transition to turbulence.

(2) The analysis is valid until the radial pressure flow approaches a Mach number of $1/\sqrt{\gamma}$, where γ is the ratio of specific heats or until the pressure flow becomes turbulent.

The objective of this report is to present the computer program for the analysis given in reference 1. Input variables include the dimensions of the seal, pressure boundary conditions, and molecular weight and physical properties of the gas. For specified film thicknesses, which are used as parametric input, the output includes mass flow rate, pressure distribution, velocity distribution, Mach number, force, center of pressure, rotational flow Reynolds number, pressure flow Reynolds number, power loss, torque, and approximate temperature rise due to the viscous shearing. The computer program is written in Fortran IV for the computer at Lewis Research Center, which is an IBM 7094II/7044 or 7040 direct couple computer under IBSYS version 13 using ALTIO. All input, calculations, and output are in English units; printout of data in the International System (SI) of units is optional.

COMPUTER ANALYSIS

Sealing Dam Model

A typical face seal is shown in figure 1. It consists of a nonrotating nosepiece held either in sliding contact against or in close proximity to a rotating seal seat; the dynamic leakage gap (sealing dam) between the nonrotating and rotating surfaces is exaggerated in

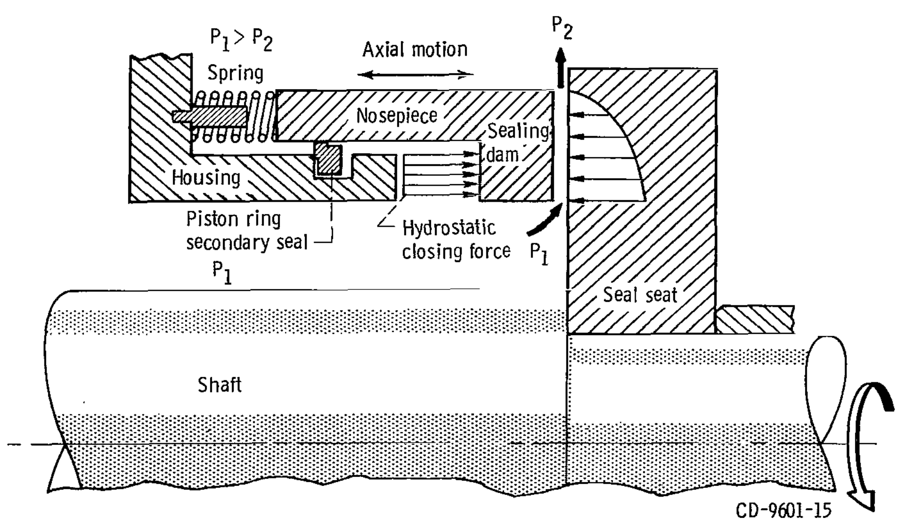


Figure 1. - Schematic of pressure balanced face seal.

the diagram. Since typical values of the sealing gap are less than 0.0010 inch (0.0025 cm), the gap is, in effect, a long narrow slot, and viscous forces are predominant in leakage analysis. The model that approximates this sealing dam is shown in figure 2. It consists of two parallel, concentric circular rings, separated by a very narrow gap, with one moving at a constant speed. A pressure differential exists between

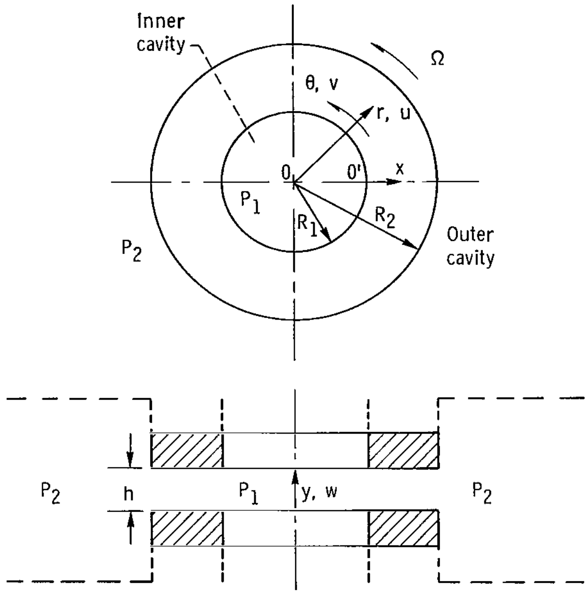


Figure 2. - Model of sealing dam.

the inner and outer diameter of the rings, and the fluid is stagnant in the inner and outer cavities that bound the sealing dam. The model formulation is based on the following restrictions:

(1) Homogeneous, compressible, viscous, and Newtonian fluid

(2) Steady and laminar flow with negligible inertia forces

(3) Bulk modulus, $\lambda = -\frac{2}{3}\mu$ (Symbols are defined in appendix A.)

(4) Perfect gas fluid

(5) Negligible entrance region effects

(6) Isothermal fluid film

(7) Entrance Mach number, close to zero

Sealing Dam Analysis

The governing flow equations for a compressible fluid with constant viscosity in vector notation are as follows (ref. 3):

Conservation of mass

$$\frac{D\rho}{Dt} + \rho\vec{\nabla} \cdot \vec{V} = 0$$

Conservation of momentum (Navier-Stokes equation)

$$\rho \frac{D\vec{V}}{Dt} = \vec{\nabla}P - \mu\vec{\nabla}x(\vec{\nabla}x\vec{V}) + (\lambda + 2\mu)\vec{\nabla}(\vec{\nabla} \cdot \vec{V}) + \vec{F}$$

Equation of state for an isothermal process

$$P = P(\rho)$$

In reference 1 the governing flow equations are applied to the sealing dam model, simplified, and solved by

(1) Utilizing a cylindrical coordinate system (see fig. 2)

(2) Simplifying the governing equations by using the restrictions listed for the sealing dam model

(3) Applying the appropriate boundary conditions.

The resulting equations are shown in table I in the form used in the computer program.

The equations of table I are in the English system of units, and table II shows the conversions to SI units. The computer calculations are carried out in the English system of units, but the program contains provision for printout in SI units.

TABLE I. - FORM OF PERTINENT EQUATIONS FOUND IN COMPUTER PROGRAM

(IN SAME SEQUENCE AS EQUATIONS APPEAR IN PROGRAM)

$$A = \pi\left(R_2^2 - R_1^2\right), \text{ in.}^2$$

$$\mathcal{R} = \frac{\underline{\mathcal{R}}}{m}, \ \frac{\text{ft-lbf}}{\text{lbm }^{\circ}\text{R}} \quad \text{where } \underline{\mathcal{R}} = 1545.4 \ \frac{\text{ft-lbf}}{(\text{lb-mole})\ ^{\circ}\text{R}}$$

$$\rho_1 = \frac{P_1(144 \text{ in.}^2/\text{ft}^2)}{\mathcal{R}(T + 460)\left(32.174 \ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}\right)}, \ \frac{\text{lbf-sec}^2}{\text{ft}^4}$$

$$a = \sqrt{\gamma\mathcal{R}(T + 460)\left(32.174 \ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}\right)}, \text{ ft/sec}$$

$$\text{If } L = 0, \ L = 2\pi \frac{(R_1 + R_2)}{2}, \text{ in.}$$

$$\text{If } \rho_0 = 0, \ \rho_0 = \rho_1, \ \text{lbf-sec}^2/\text{ft}^4$$

$$\text{If } N \neq 0, \ V = \frac{2\pi N}{(12 \text{ in./ft})}\left(\frac{R_1 + R_2}{2}\right)\left(\frac{\text{min}}{60 \text{ sec}}\right), \text{ ft/sec}$$

$$\begin{array}{lll} \text{If } N = 0 & & \Delta T = 0, \ ^{\circ}\text{R} \\ \text{and if } V = 0, & \text{then} & C_p = 0, \ \text{Btu/lbm }^{\circ}\text{R} \end{array}$$

$$\Omega = 2\pi N, \text{ rad/min}$$

$$\text{Re}(\bar{R}) = \rho_0\left(\frac{R_2 + R_1}{2}\right)\frac{\Omega}{\mu}\ \frac{h}{(60 \text{ sec/min})(144 \text{ in.}^2/\text{ft}^2)}$$

$$\Delta X = \frac{R_2 - R_1}{(\text{number of steps})}, \text{ in.}$$

$$\dot{M} = \frac{1.93\times10^3 h^3 \rho_1\left\{P_1^2 - P_2^2 \exp\left[-\frac{K_1}{2}\left(\frac{R_1^2}{R_2^2} - 1\right)\right]\right\}\exp\left(\frac{K_1}{2}\ \frac{R_1^2}{R_2^2}\right)}{\mu P_1 \displaystyle\int_0^{R_2-R_1} \frac{\exp\left[\frac{K_1}{2}\left(\frac{x + R_1}{R_2}\right)^2\right]}{x + R_1}\,dx}, \text{ lb/min}$$

$$\text{where } K_1 = -\frac{3}{5}\ \frac{R_2^2\Omega^2}{\mathcal{R}T}$$

$$U_{av}(x) = \frac{(144 \text{ in.}^2/\text{ft}^2)}{\left(32.174 \frac{\text{lbm-ft}}{\text{lbf-sec}^2}\right)\left(60 \ \frac{\text{sec}}{\text{min}}\right)}\ \frac{\dot{M} P_1}{L\rho_1 h_1 P(x)}, \text{ ft/sec}$$

$$M = \frac{U_{av}}{a}$$

$$\text{Re}(P) = \frac{P_{min} U_{av} 2h(12 \text{ in./ft})}{\left(32.174 \ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}\right)\mu\,\mathcal{R}(T + 460)} = \text{Re}_{2h}$$

$$Q = 13.083\,\dot{M}, \text{ scfm}$$

$$\text{Power} = \frac{\mu A V^2}{h}\left(\frac{1 \text{ hp}}{550 \ \frac{\text{ft-lb}}{\text{sec}}}\right)\left(\frac{1}{12 \ \frac{\text{in.}}{\text{ft}}}\right), \text{ hp}$$

$$\Delta T = \frac{\left(42.42 \ \frac{\text{lbf-min}}{\text{hp}}\right)(\text{Power})}{\dot{M} C_p}, \ ^{\circ}\text{F}$$

$$H_{TOT} = 42.42 \ (\text{Power}), \text{ Btu/min}$$

$$F = L\int_0^{R_2-R_1}(P - P_{min})\,dx, \text{ lbf}$$

$$X_c = \frac{L}{F}\int_0^{R_2-R_1}(P - P_{min})\,x\,dx, \text{ in.}$$

$$x = x_1 + n\Delta x, \text{ in.}$$

$$P(x) = \left\{\exp\left[-\frac{K_1}{2}\left(\frac{x + R_1}{R_2}\right)^2\right]\left[\frac{P_2^2 \exp\left(\frac{K_1}{2}\right) - P_1^2 \exp\left(\frac{K_1 R_1^2}{2R_2^2}\right)}{\displaystyle\int_0^{R_2-R_1}\frac{\exp\left[\frac{K_1}{2}\left(\frac{x + R_1}{R_2}\right)^2\right]}{x + R_1}\,dX} \times \int_0^{x}\frac{\exp\left[\frac{K_1}{2}\left(\frac{x + R_1}{R_2}\right)^2\right]}{x + R_1}\,dx + P_1^2 \exp\left(\frac{K_1 R_1^2}{2R_2^2}\right)\right]\right\}^{1/2}$$

$$\text{where } K_1 = -\frac{3R_2^2\Omega^2}{5\mathcal{R}T}$$

$$\bar{F} = \frac{F}{|P_1 - P_2|(R_2 - R_1)L}$$

$$\bar{X}_c = \frac{X_c}{(R_2 - R_1)}$$

$$\text{Torque} = \frac{(33\,000)\ (\text{Power})}{N}\left(\frac{12 \text{ in.}}{\text{ft}}\right), \text{ ft-lbf}$$

TABLE II. - CONVERSION TO INTERNATIONAL UNITS

Quantity	To convert		Multiply by
	From	To	
Length	in.	m	2.54×10^{-2}
Mass	lbm	kg	0.45359239
Time	min	sec	60
Force	lbf	N	4.4482216
Torque	lbf-ft	m-N	1.3558179
Energy	Btu	J	1.05587×10^{3}
Power	hp	W	7.4569987×10^{2}
Density	$lbf\text{-}sec^2/ft^4$	kg/m^3	5.15379×10^{2}
Viscosity	$lbf\text{-}sec/ft^2$	$N\text{-}sec/m^2$	47.880258
Gas constant	$ft\text{-}lbf/lbm\text{-}^oR$	J/kg-K	5.38095
Specific heat	$Btu/lbm\text{-}^oR$	J/kg-K	4.1865783×10^{3}
Temperature	^oF	K	K = 5(F + 460)/9
Temperature difference	^oF	K	K = 5F/9
Pressure	psi	N/m^2	6.8947572×10^{3}
Velocity	rpm	rps	1/60
	ft/sec	m/sec	0.3048
Area	$in.^2$	m^2	6.4516×10^{-4}
Mass flow rate	lbm/min	kg/sec	7.55987×10^{-3}
Volume flow rate at standard conditions	scfm	m^3/sec	4.7194744×10^{-4}
Heat flow rate	Btu/min	W	17.59783

Also included are lists of the input variables and program variables along with their descriptions and English units, detailed descriptions of the subprograms, and a flow chart of the main program (fig. 3). (Listings of the programs are given in appendix B; the sample problem, with output options, appears in appendix C.)

Description of Program

RSEAL - Main Program. - The main program, RSEAL, performs the primary flow analysis. Subroutines are used for secondary operations such as numerical integrations and plotting data. Input to RSEAL is by punched cards in the following order:

(1) Title card: alphanumeric identification of the data (format 12A6)

(2) NJ card: number of film thicknesses to be analyzed in one running of the program (format I3)

(3) Film thickness, h_m, cards: 6 per card (format 6F12.0)

(4) Data cards: seal dimensions, operating conditions, physical properties of gas and logical variables (read by NAMELIST/RINPT/)

Data are read by NAMELIST to minimize the number of cards required to run a second case with the same title and h_m cards. Input variables are set of zero initially.

Consequently, variables that are not changed during the reading of data will be calculated by the program. (See the list of input variables for the significance of each variable and any restrictions on them.)

Output data are printed in English units in the following order of groups:

(1) Program identification: compressible sealing dam with rotation and parallel surfaces

(2) Data identification: printout of title card

(3) Input data as it appears on RINPT cards

(4) Calculated constants: gas constant, reference density, speed of sound, length of seal, area of seal

(5) Parameters that vary with h_m: mass flow rate, volume flow rate at standard conditions, maximum Mach number, pressure flow Reynolds number, rotational flow Reynolds number, sealing dam force, center of pressure, dimensionless sealing dam force, dimensionless center of pressure, and Knudsen number. (Printout of dimensionless sealing dam force and center pressure may be skipped by setting RSKIP to TRUE.)

(6) Parameters associated with power dissipation: power, total shear heat, apparent temperature rise, and torque. (Printout of all data associated with power dissipation may be skipped by setting TSKIP to TRUE.)

(7) Distribution of parameters across the sealing dam (one group for each h_m): distance across seal, pressure, pressure ratio, average velocity, and Mach number.

Printout of data in English units is followed by plots of various parameters. Plots appear in standard form with minimum X and minimum Y in the lower left-hand corner. Legends at the bottom of the plots give conversion factors for SI units. The plots are as follows:

(1) Power versus h_m for $N \neq 0$

(2) Pressure ratio versus distance across seal for first case for which the model is valid. Plot 2 may be suppressed by setting ASKIP to TRUE.

Following the plots, the data are printed in SI units in the same order as for English units. This printout may be skipped entirely by setting NOUI to TRUE.

RSEAL is divided roughly into eight sections. The first section reads data and calculates program constants (cards 41 to 56).

Section two (cards 82 to 87) calculates the constants needed in the pressure equation.

Section three (cards 93 to 105) tests input variables. If they are zero, new values for them are calculated. Since SPEED and CAPV both represent rotational velocity, they must be consistent. If SPEED is read as nonzero, CAPV is calculated from SPEED. If SPEED is read as zero, CAPV must be examined. In the case that CAPV is nonzero, SPEED is calculated from CAPV. If both SPEED and CAPV are zero, the system considered is static.

Section four (cards 111 to 139) is the first part of a loop which is done for each h_m. This section calculates a starting value for X, mass flow rate, volume flow rate at standard pressure condition, pressure flow Reynolds number, rotational flow Reynolds number, maximum Mach number, and Knudsen number. If the maximum Mach number is greater than $1/\sqrt{\gamma}$, this analysis is no longer valid, IHTAG(J) is set equal to 1 as a trigger, and no further calculations are made. If the model remains valid, the program calculates power, temperature rise due to power dissipation, total shear heat, sealing dam force, and center of pressure. The integrations in the force and center of pressure equations are done numerically by Simpson's Rule.

Section five (cards 144 to 154) is the rest of the loop started in section three. Section five calculates pressure, pressure ratio, average velocity, and Mach number for several points across the sealing dam.

Section six (cards 158 to 200) writes data in English units. Section seven (cards 204 to 233) plots the various parameters. And section eight (cards 237 to 295) writes data in SI units.

Numerical constants in the program are for units conversion.

Subprograms. - RSEAL uses eight subprograms whose listings appear in appendix B. These are SIMPS1, SIMPS2, PX, PXX, PRESS, ROT, EXPK, and ARRNG. RSEAL also uses two other subroutines that are not standard in IBSYS: SORTXY and PLOTXY.

SORTXY sorts two numerical arrays. A statement such as CALL SORTXY (X, Y, N) results in the array X being rearranged such that $X(1) \leq X(2) \leq . . . \leq X(N)$ with the Y array entries reordered to preserve the (X, Y) pairs. N is the number of elements in the X and Y arrays.

PLOTXY plots two numerical arrays. A statement such as CALL PLOTXY (X, Y, KODE, P) produces a printer plot of X versus Y with the minimum X and the minimum Y in the upper left corner of the page with X increasing down the page and Y increasing across the page. KODE tells which plotting options are to be used. For example, KODE = 6 gives a plot with most of the grid lines suppressed, with asterisks as the plotting character, and with the X and Y scales computed by the plotting routine. The array P contains information needed by the plotting routine such as the number of points to be plotted, the X and Y scales if the programmer computes them, and the frequency of grid lines in the X and Y directions.

Special format statements are used to print plot titles and plot legends. A pair of statements such as

```
WRITE (6,1)
1 FORMAT (2HPT, 10HPLOT TITLE)
```

will print the title

PLOT TITLE

above the plot. A pair of statements such as

```
WRITE (6, 2)
2 FORMAT (2HPL, 11HPLOT LEGEND)
```

will print the legend

PLOT LEGEND

immediately below the plot.

Listings of SORTXY AND PLOTXY along with details for their use can be found in reference 4 or can be obtained from the Instrument and Computing Division of the Lewis Research Center.

SIMPS1 is a function subprogram to perform a numerical integration by Simpson's Rule. The integrand is evaluated at interior points by the external function named in the calling vector. A statement such as F = SIMPS1 (XO, XF, G, K) gives F as the definite integral

$$\int_{XO}^{XF} G(X)\, dX$$

The integrand is evaluated at interior points by the function G named in the calling vector. The interval of integration XO to XF is not divided uniformly. More subdivisions are made where values of the integrand are changing rapidly. If two successive evaluations of the integral on a particular subinterval differ by more than $3\times10^{-5}\times$ value of the integrand, the subinterval is divided into two subintervals and the integration is repeated. If the integration required more than 200 subintervals, the integer K is raised by 1 to indicate that the value of the integral is incorrect.

SIMPS2 performs essentially the same operation as SIMPS1, but it permits carrying a constant parameter into the integration by means of the calling vector. A statement such as F = SIMPS2 (A, XO, XF, G, KK) gives F as the indefinite integral

$$\int_{XO}^{XF} G(A, X)\, dX$$

Use of SIMPS2 permits evaluating double integrals because the external function G can call SIMPS1 to evaluate the inner integral. KK performs the same function as K, but KK is raised by 2 to indicate inaccuracies in the integration. Subprograms SIMPS1 and SIMPS2 are in general use at the Lewis Research Center.

PRESS is a function subprogram to evaluate the pressure at any distance from the inner radius of the seal. This distance appears in the calling vector. The pressure differential equation is solved analytically and the resulting formula is used in the program.

$$P(x) = \left\{ \exp \frac{-K_1}{2} \left(\frac{x + R_1}{R_2} \right)^2 \left[\frac{P_2^2 \exp\left(\frac{K_1}{2}\right) - P_1^2 \exp\left(\frac{K_1 R_1^2}{2R_2^2}\right)}{\displaystyle\int_0^{R_2 - R_1} \frac{\exp\left[\frac{K_1}{2}\left(\frac{x + R_1}{R_2}\right)^2\right]}{x + R_1} dx} \int_0^x \frac{\exp\left[\frac{K_1}{2}\left(\frac{x + R_1}{R_2}\right)^2\right]}{x + R_1} dx + P_1^2 \exp\left(\frac{K_1 R_1^2}{2R_2^2}\right) \right] \right\}^{1/2}$$

where PX is an external function to evaluate the integrand in the integral

$$\frac{F}{L} = \int_0^{R_2 - R_1} (P - P_{min})\, dx$$

Similarly, PXX is an external function to evaluate the integrand in the integral

$$X_c = \frac{L}{F} \int_0^{R_2 - R_1} (P - P_{min})\, x\, dx$$

where P_{min} is the smaller of P_1 and P_2.

EXPK is a function subprogram to evaluate $\exp(K_1 x)/(2R_2^2)$ where x appears in the calling vector.

ROT is an external function to evaluate the integrand in the integral

$$\int_0^X \frac{\exp\left[\frac{K_1(x + R_1)^2}{2R_2^2}\right]}{x + R_1} dx$$

ARRNG is a subroutine subprogram which arranges two arrays X and Y for plotting. The subroutine first eliminates cases for which the model does not remain valid. It then sorts the remaining data in order of ascending X. It then inverts both arrays and interchanges them. The data are now in the form of ordered pairs (Y(N), X(N)), (Y(N - 1), X(N - 1), . . ., (Y(1), X(1)) where $Y(N) \geq Y(N-1) \geq . . . \geq Y(1)$. Data arranged in this form permit plotting with Y as the independent variable in descending order. Consequently, the plots appear with the minimum X and minimum Y in the lower left corner.

Input Variables

The following table lists variables input to the program and their units. Arrays are given with their dimensions.

Variable	Unit	Description
TITLE (12)		Data identification
NJ		Number of mean film thicknesses ($NJ \leq 50$)
HMEAN(J), J=1, NJ	in.	Mean film thicknesses
L	in.	Width or mean circumference of sealing dam of flow
SPEED	rpm	Rotational speed. Either SPEED or CAPV may be set. If both are set, calculate CAPV from SPEED
CAPV	ft/sec	Surface speed.
MOLWT	lbm/(lb-mole)	Molecular weight of the gas
P1	psi	Pressure at inner radius of seal
P2	psi	Pressure at outer radius of seal
T	^{o}F	Isothermal reference temperature

Variable	Unit	Description
R1	in.	Inner radius of seal
R2	in.	Outer radius of seal
RHORO	$lbf\text{-}sec^2/ft^4$	Reference density at inner radius of the seal. If RHORO is read as zero, program calculates RHORO.
RHORF	$lbf\text{-}sec^2/ft^4$	Density at mean radius used in calculating the rotational Reynolds number. If RHORF is read as zero, the program calculates RHORF.
MU	$lbf\text{-}sec/ft^2$	Absolute viscosity of gas
CP	$Btu/lbm\text{-}{}^oR$	Specific heat of gas
GAMMA		Ratio of specific heats
NGRID		Number of steps across seal (max = 20)
ASKIP		Logical variable. If ASKIP = TRUE, program skips calculation and printout of x, pressure, average velocity, Mach number, and pressure ratio. It also skips plotting of x versus pressure ratio.
RSKIP		Logical variable. If RSKIP = TRUE, program skips calculation and printout of dimensionless center of pressure and force. It also skips plotting of dimensionless F.
TSKIP		Logical variable. If TSKIP = TRUE, program skips calculation, printout, and plotting of power.
NOUI		Logical variable. If NOUI = TRUE, program makes no conversion to SI units.

Program Variables

The following table lists the variables used in the program in the approximate order of their appearance, any limitations on the variables, and their units. Variables marked with an asterisk are printed as output data.

PI		$\pi = 3.1415927$
RUNIV	$ft\text{-}lbf/(lb\text{-}mole)^oR$	Universal gas constant

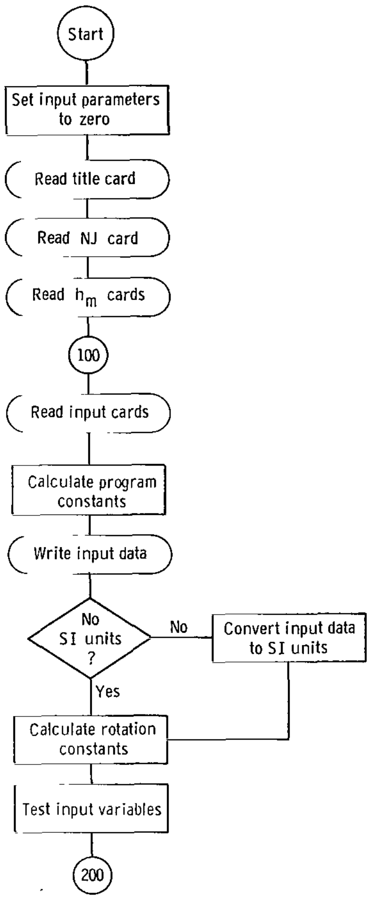
Variable	Unit	Description
ZERO		Input variables are set to 0.
PREF	psi	Smaller of P1 and P2 in the COMMON block
RR1	in.	Value of R1 in the COMMON block
MCUT		$1/\sqrt{\gamma}$ = upper limit for which model is valid
NN		Number of grid points ($1 \leq NN \leq 21$)
JMOD		Integer number of pressure distributions that will fit on one page.
RDIF	in.	Distance across seal = R2-R1
PDIF	psi	Total pressure drop across seal
AREA*	$in.^2$	Face surface area of seal
R*	$lbf\text{-}ft/lbm\text{-}^{o}R$	Gas constant
RHO1*	$lbf\text{-}sec^2/ft^4$	Density at inner radius of seal
A*	ft/sec	Speed of sound
RHOREF*	$lbf\text{-}sec^2/ft^4$	Calculated density at mean radius of seal
OMEGA	rad/min	Rotational velocity
ECONST	$1/in.^2$	$-K_1/2R_2^2$ (where K_1 is defined in appendix A)
EA	$lbf^2/in.^4$	$P_1^2 \exp \frac{K_1}{2}\left(\frac{R_1}{R_2}\right)^2$
AA	$lbf^2/in.^4$	$P_2^2 \exp \frac{K_1}{2} - P_1^2 \exp \frac{K_1}{2}\left(\frac{R_1}{R_2}\right)^2$
S		$\int_0^{R_2-R_1} \frac{\exp\left[\frac{K_1}{2}\left(\frac{X+R_1}{R_2}\right)^2\right]}{X+R_1} dX$
DELX	in.	Distance between two successive grid points
X(J, I)*	in.	Distance from inner radius of seal
MDOT(J)*	lbm/min	Mass flow rate
VAV	ft/sec	Average velocity at outer radius of seal
MACHMX(J)*		Maximum Mach number for given HMEAN
REP(J)*		Pressure flow Reynolds number

Variable	Unit	Description
RER(J)*		Rotational flow Reynolds number
Q(J)*	scfm	Volume flow rate at standard conditions
KN(50)*		Knudsen number
IHTAG(J)		Numerical flag IHTAG(J) = 0 implies model remains valid IHTAG(J) $\neq$ 0 implies model is invalid
POWER(J)*	hp	Power dissipated by viscous shearing
DELTJ(J)*	^{o}F	Apparent temperature rise due to power dissipation
TORQUE(J)*	lbf-ft	Torque
HTOTAL(J)*	Btu/min	Total shear heat of system
F(J)*	lbf	Equivalent force
XC(J)*	in.	Center of pressure
K, KK		Numerical flags that indicate whether the numerical integrations in the calculation of F(J) and XC(J) are accurate
P(J, I)*	psi	Pressure at X(J, I)
PRAT(J, I)*		Ratio of P to P_{min} at X(J, I)
UAVRG(J, I)*	ft/sec	Average velocity at X(J, I)
MACH(J, I)*		Mach number at X(J, I)
FBAR(J)*		Dimensionless force
XCBAR(J)*		Dimensionless center of pressure
JJ		Counter for valid cases. If JJ = 1 modulo JMOD, the printer will skip to a new page.
XPT(50), YPT(50), XPLOT(50), YPLOT(50)		Utility arrays used in sorting and plotting data
PP(61)		Array needed by plotting subroutine - see description of PLOTXY for details
KODE		Plotting code - see description of PLOTXY for details
NP		Number of points in a plot (1 $\leq$ NP $\leq$ 50)
I		X index
J		HMEAN index

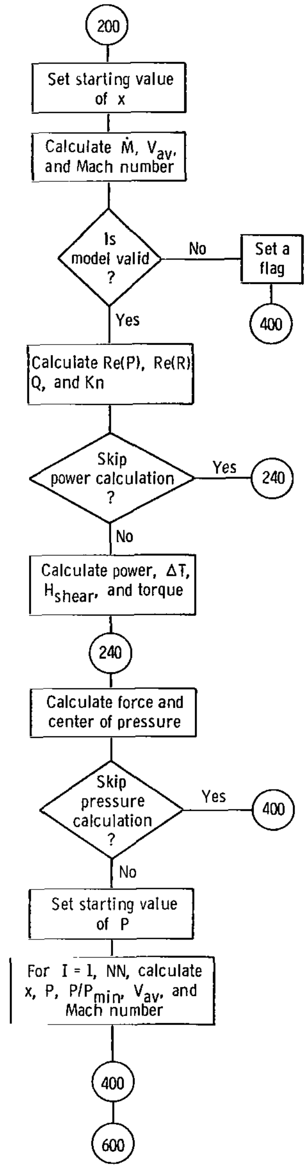
Subroutines

Name	Call vector variables	Common block variables	Program variables	Description
PRESS - pressure function	X			Distance from inner radius of seal
		PREF		Reference pressure
		RR1		Inner radius of seal
		EA		$P_1^2 \exp \frac{K_1}{2}\left(\frac{R_1}{R_2}\right)^2$
		AA		$P_2^2 \exp \frac{K_1}{2} - P_1^2 \exp \frac{K_1}{2}\left(\frac{R_1}{R_2}\right)^2$
		S		$\int_0^{R_2-R_1} \frac{\exp \frac{K_1}{2}\left(\frac{X+R_1}{R_2}\right)^2}{X+R_1} dx$
			R1	Inner radius of seal
			QQ	$\int_0^{X} \frac{\exp \frac{K_1}{2}\left(\frac{X+R_1}{R_2}\right)^2}{X+R_1} dx$
			K	Numerical flag indicates whether numerical integration is accurate
			Q	$P^2(x)$
ROT - integrand in integral $\int_0^{X} \frac{\exp -\frac{K_1}{2}\left(\frac{X+R_1}{R_2}\right)^2}{X+R_1} dx$	R1			Inner radius of seal
	X			Distance from inner radius of seal
			Y	Radial distance = R1 + x
PX - integrand in integral $\int_0^{R_2-R_1} (P - P_{min})\, dx$	X			Distance from inner radius of seal
		PREF		Reference pressure
		A, B, C, D		Dummy variables to fill COMMON block
			Y	$P - P_{min}$

Name	Call vector variables	Common block variables	Program variables	Description
PXX - integrand in integral $\int_0^{R_2-R_1} (P - P_{min})\, x\, dx$	X			Distance from inner radius of seal
		PREF		Reference pressure
		A, B, C, D		Dummy variables to fill COMMON block
			Y	$(P - P_{min})X$
EXPK - special exponential function	X			Square of distance from center of seal
		ECONST		$(K_1/2)/R_2^2$
			YY	Distance from center of seal
			Y	$\exp\left[\frac{K_1}{2}\left(\frac{x + R_1}{R_2}\right)^2\right]$
ARRNG - arranges arrays in proper order for plotting	X			Input array of independent variables
	Y			Input array of dependent variable
	XP			Sorted and inverted array of new independent variable
	YP			Sorted and inverted array of new dependent variable
	N			Number of elements in input arrays
	I			Number of elements in sorted arrays
			T	Temporary storage for sorting

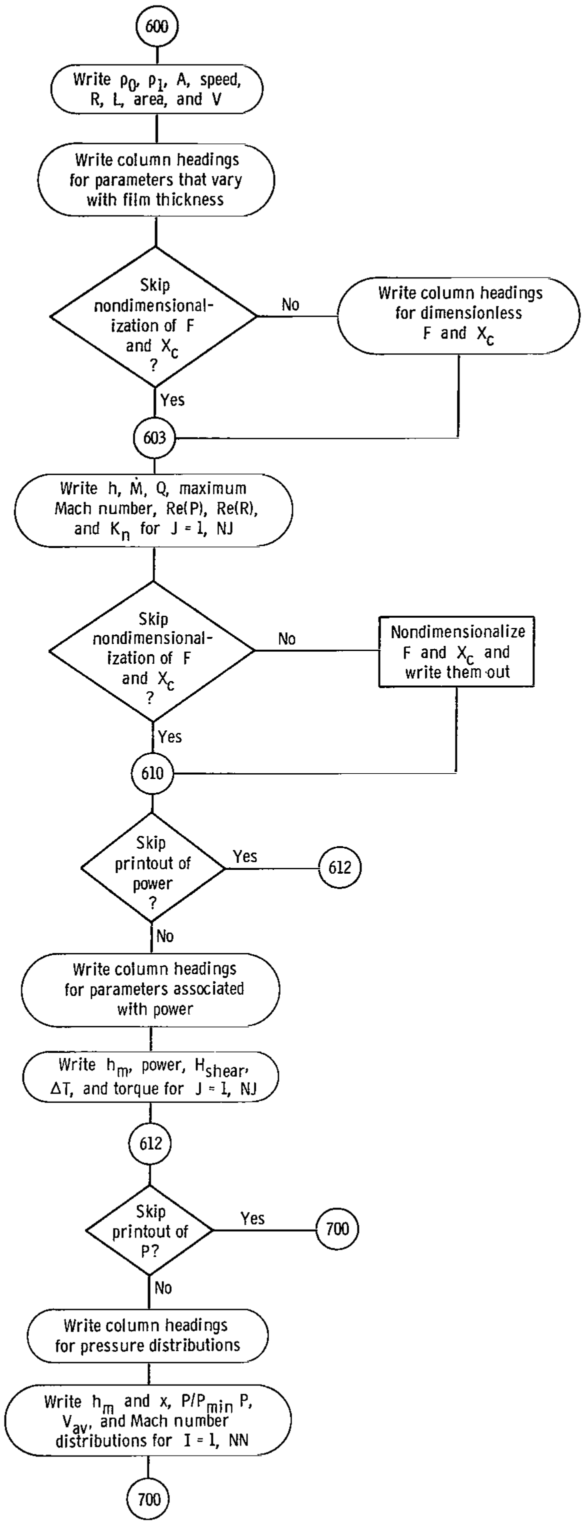


(a) Initial steps.



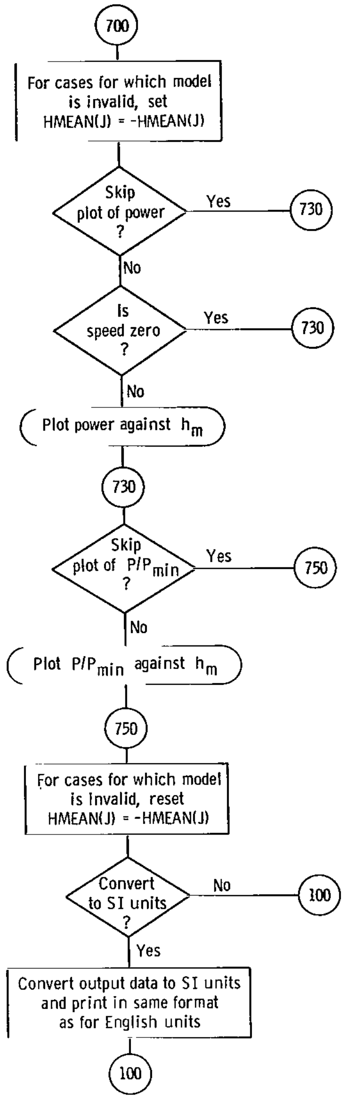
(b) Main calculation.

Figure 3. - Flow chart of Main Program.



(c) Write routine.

Figure 3. - Continued.



(d) Plot routine.

Figure 3. - Concluded.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 24, 1969,
120-27-04-90-22.

APPENDIX A

SYMBOLS

A	cross-sectional area, in.^{2}; m^2
a	speed of sound, ft/sec; m/sec
C_p	specific heat at constant pressure, Btu/(lbm)(^oR); J/(kg)(K)
C_v	specific heat at constant volume, Btu/(lbm)(^oR); J/(kg)(K)
D/Dt	material derivative, $\frac{\partial}{\partial t} + u \frac{\partial}{\partial r} + \frac{v\partial}{r\partial\theta} + w \frac{\partial}{\partial z}$
F	sealing dam force, lbf; N
$\bar{F}$	dimensionless force, $F/(P_2 - P_1)(R_2 - R_1)L$
$\vec{F}$	body force vector
h	film thickness, nominal, in.; m
K_1	$-(3R_2^2\Omega^2/5\mathcal{R}T)$
L	sealing dam width, in.; m
M	Mach number
$\dot{M}$	mass flow, lbm/min; kg/sec
$\Delta\dot{M}$	change in mass flow
m	molecular weight of gas, lbm/(lb-mole); kg/kg-mole
N	speed of rotation, rpm
n	integer
P	static pressure, psi; N/m^2
ΔP	pressure differential, psi; N/m^2
P_{min}	smaller pressure of two pressure boundary conditions, psi; N/m^2
Q	net volume flow rate, scfm; std. m^3/sec
$\bar{R}$	mean radius, $(R_1 + R_2)/2$, in.; m
ΔR	sealing dam length, $R_2 - R_1$, in.; m
Re_h	Reynolds number in radial direction, $\rho Uh/\mu$
Re_r	Reynolds number in circumferential direction, $\rho\bar{R}\Omega h/\mu$
$\mathcal{R}$	gas constant, $\underline{\mathcal{R}}/m$, ft-lbf/(lbm)($^oR$); J/(kg)(K)
$\underline{\mathcal{R}}$	universal gas constant, 1545.4 ft-lbf/(lb-mole)(^oR); 8.3143 J/(kg-mole)(K)
r	radial direction coordinate
T	temperature, ^oF; K
$\bar{T}$	average temperature, ^oF, K
U	pressure-flow reference velocity, ft/sec; m/sec
u	velocity in r-direction or x-direction, ft/sec; m/sec
V	reference shear flow velocity, ft/sec; m/sec
v	velocity in θ-direction, ft/sec; m/sec
w	velocity in y-direction, ft/sec; m/sec
W	reference velocity across film thickness, $U(h/\Delta R)$, ft/sec; m/sec

X_c center of pressure in radial or x-direction, in.; m

$\overline{X}_c$ dimensionless center of pressure, $X_c/(R_2 - R_1)$

x coordinate in pressure gradient direction

y coordinate across film thickness

z shear flow coordinate in Cartesian system

γ specific-heat ratio, C_p/C_v

θ circumferential coordinate

λ second viscosity coefficient or coefficient of bulk viscosity

μ absolute or dynamic viscosity, (lbf)(sec)/ft^2; (N)(sec)/m^2

ν kinematic viscosity, ft^2/sec; m^2/sec

ρ density, (lbf)(sec^2)/ft^2; kg/m^3

Ω angular rotational velocity, rad/sec

∇ Del operator, $\frac{\partial}{\partial r}\hat{i} + \frac{1}{r}\frac{\partial}{\partial \theta}\hat{j} + \frac{\partial}{\partial z}\hat{k}$

Subscripts:

av average

h based on film thickness

m mean

r based on radius

ref reference

0 reference

1 inner radius or inlet

2 outer radius or exit

APPENDIX B

PROGRAM LISTING

```
$IBFTC RSEAL    DEBUG
C
C      COMPRESSIBLE FLOW SEALING DAM ANALYSIS WITH ROTATION)
C
       LOGICAL ASKIP,RSKIP,TSKIP,NOUI
       REAL MDOT,MOLWT,MU,MACH,MACHMX,MCUT,KN,L
       DIMENSION XPLOT(50),YPLOT(50),XPT(50),YPT(50),PP(61),ZERO(17),
      1  UI(30),TITLE(12)
       DIMENSION F(50),XC(50),MDOT(50),XCBAR(50),FBAR(50),Q(50),
      1 POWER(50),HI(50),HTOTAL(50),DELTJ(50),TORQUE(50),HMEAN(50),
      2 MACHMX(50),REP(50),IHTAG(50),KN(50),RER(50)
       DIMENSION X(50,21),P(50,21),UAVRG(50,21),PRAT(50,21),MACH(50,21)
       COMMON/INTGRL/PREF,RR1,EA,AA,S
       COMMON/ECON/ECONST
       EXTERNAL PX,PXX,ROT
       NAMELIST/RINPT/L,SPEED,CAPV,MOLWT,P1,P2,T,R1,R2,RHORO,
      1 RHORF,MU,CP,GAMMA,NGRID,ASKIP,RSKIP,TSKIP,NOUI
       DATA PI,RUNIV/3.1415927,1545.4/
       EQUIVALENCE (ZERO(1),MOLWT),  (ZERO(6), P1),    (ZERO(11),L),
      1              (ZERO(2),SPEED),  (ZERO(7), P2),    (ZERO(12),T),
      2              (ZERO(3),RHORO),  (ZERO(8), R1),    (ZERO(13),MU),
      3              (ZERO(4),RHORF),  (ZERO(9), R2),    (ZERO(14),CAPV),
      4              (ZERO(5),GAMMA),  (ZERO(10),CP)
       DO 90 I=1,14
    90 ZERO(I) = 0.
C
C      READ INPUT DATA,CALCULATE PROGRAM CONSTANTS, AND WRITE INPUT
C      CONDITIONS
C
C      DATA CARDS
C            TITLE - DATA IDENTIFICATION - 1 CARD (FORMAT 12A6)
C
C               NJ - NUMBER OF FILM THICKNESSES (FORMAT I3)
C
C            HMEAN - MEAN FILM THICKNESSES - 6 PER CARD (FORMAT 6F12.0)
C
C           $RINPT - SEAL DIMENSIONS, OPERATING CONDITIONS, PHYSICAL
C                    PROPERTIES OF GAS, LOGICAL VARIABLES
C                    (READ BY NAMELIST/RINPT/)
C
       READ (5,3) TITLE
       READ (5,1) NJ
       READ (5,2) (HMEAN(J),J=1,NJ)
   100 WRITE (6,10)
       READ (5,RINPT)
       PREF = AMIN1(P1,P2)
       RR1 = R1
       MCUT = 1./SQRT(GAMMA)
       NN = NGRID+1
       JMOD = 59/(4+NN)
       AREA = PI*(R2**2-R1**2)
       RDIF=R2-R1
       PDIF=ABS(P1-P2)
       R= RUNIV/MOLWT
       RHO1= P1/R/(T+460.)*4.4756636
       A= SQRT(GAMMA*R*(T+460.)*32.174)
       WRITE (6,54) TITLE
       WRITE(6,11) P2,P1,T,MU,MOLWT,GAMMA,R2,R1,L,RHORO,RHORF,NN,
      1 SPEED,CAPV,CP,ASKIP, RSKIP,TSKIP
       IF (NOUI) GO TO 110
```

```
C
C     CONVERT INPUT DATA TO INTERNATIONAL UNITS
C
      UI(1) = ALPHA
      UI(2) = P2*6.894757 2E3
      UI(3) = P1*6.894757 2E3
      UI(4) = (T+460.)/1.8
      UI(5)= MU*47.880258
      UI(6)= MOLWT
      UI(7) = GAMMA
      UI(8) = R2*2.54E-2
      UI(9) = R1*2.54E-2
      UI(10) = L*2.54E-2
      UI(11) = RHORO*517.2026
      UI(12) = RHORF*517.2026
      UI(13) = SPEED/60.
      UI(14)= CAPV*.3048
      UI(15) = CP*.41865783E4
C
C     DETERMINE ROTATION CONSTANTS
C
  110 OMEGA = 2.*PI*SPEED
      ECONST = -.3*OMEGA**2/R/(T+460.)/3600./32.174/144.
      EA = EXPK(R1**2)*P1**2
      AA = EXPK(R2**2)*P2**2-EA
      K = 0
      S = SIMPS2(R1,0.,RDIF,ROT,K)
      IF (K.NE.0)    WRITE (6,21)
      DEBUG OMEGA,ECONST,EA,AA,S
C
C     TEST INPUT PARAMETERS AND DETERMINE OPERATING CONDITONS
C
  120 IF (L.EQ.0.)        L=P1*(R1+R2)
      IF(RHORO.NE.0.) RHO1=RHORO
      IF (RHORF.NE.0.)    GO TO 123
      RHOREF = PRESS(RDIF/2.)/R/(T+460.)*4.4756636
      GO TO 124
  123 RHOREF = RHORF
  124 IF (SPEED.EQ.0.)    GO TO 121
      CAPV = PI*SPEED*(R1+R2)/720.
      GO TO 122
  121 IF (CAPV.NE.0.)    GO TO 122
      TSKIP = .TRUE.
      CP = 0.
  122 SPEED = CAPV*720./PI/(R1+R2)
C
C     DETERMINE STARTING VALUES FOR X AND H
C     DETERMINE X INCRIMENT, M(DOT), Q, POWER, MAX MACH NUMBER,
C     PRESSURE REYNOLD'S NUMBER, DELTA T, HEAT(IN), AND HEAT(TOTAL)
C
  200 DO 400 J=1,NJ
      IHTAG(J) = 0
      DELX = RDIF/FLOAT(NGRID)
      X(J,1) = 0.
      MDOT(J) = -13.405833*PI*HMEAN(J)**3*RHO1*AA/MU/P1/S
      DEBUG HMEAN(J),MDOT(J)
      VAV = ABS(MDOT(J))*P1/L/RHO1/HMEAN(J)/PREF/13.405833
      MACHMX(J) = VAV/A
      IF (MACHMX(J).LT.MCUT)   GO TO 223
      IHTAG(J) = 1
```

```
      GO TO 400
  223 REP(J) = 2.*PREF*VAV*HMEAN(J)/MU/R/(T+460.)/2.6811667
  222 RER(J) = RHOREF*CAPV*HMEAN(J)/MU/12.
      Q(J) = 13.083*MDOT(J)
      KN(J) = 2.96*MACHMX(J)/REP(J)
  230 IF (TSKIP)   GO TO 240
      POWER(J)= MU*AREA*CAPV**2/HMEAN(J)/6600.
      DELTJ(J)=42.42*POWER(J)/ABS(MDOT(J))/CP
      HTOTAL(J) = 42.42*POWER(J)
      TORQUE(J)= POWER(J)*3.3E4/SPEED
C
C     DETERMINE FORCE AND CENTER OF PRESSURE
C
  240 K = 0
      KK = 0
      F(J)= SIMPS1(0.,RDIF,PX,K)*L
      XC(J) = SIMPS1(0.,RDIF,PXX,KK)/F(J)*L
      IF (K.NE.0)   WRITE (6,24) HMEAN(J)
      IF (KK.NE.0)   WRITE (6,25) HMEAN(J)
C
C     DETERMINE PRESSURE, FILM THICKNESS, PRESSURE RATIO (P/P1),
C     AVERAGE VELOCITY, AND MACH NUMBER AT EACH GRID POINT
C
  300 IF (ASKIP)      GO TO 400
      P(J,1) = P1
      DO 320 I=1,NN
      IF (I.EQ.1)      GO TO 310
      X(J,I) = FLOAT(I-1)*DELX+X(J,1)
      P(J,I) = PRESS(X(J,I))
  310 PRAT(J,I) = P(J,I)/PREF
      UAVRG(J,I)= ABS(MDOT(J))*P1/L/RHO1/P(J,I)/HMEAN(J)/13.405833
      MACH(J,I) = UAVRG(J,I)/A
  320 CONTINUE
  400 CONTINUE
C
C     WRITE ROUTINE
C
  600 WRITE (6,12) RHOREF,RHO1,A,SPEED,R,L,AREA,CAPV
      WRITE(6,13)
      IF (.NOT.RSKIP)  WRITE(6,14)
      WRITE (6,55)
      IF (RSKIP) GO TO 603
      WRITE (6,56)
C
  603 DO 610 J=1, NJ
      WRITE (6,23) HMEAN(J)
      IF (IHTAG(J).EQ.0)   GO TO 609
      WRITE (6,20)
      GO TO 610
  609 WRITE (6,15) MDOT(J),Q(J),MACHMX(J),REP(J),RER(J),KN(J),F(J),XC(J)
      IF (RSKIP)      GO TO 610
C
C     NORMALIZE F AND XC
C
      FBAR(J)=F(J)/PDIF/RDIF/L
      XCBAR(J)=XC(J)/RDIF
      WRITE(6,16) XCBAR(J),FBAR(J)
  610 CONTINUE
      IF (TSKIP) GO TO 612
      WRITE (6,17)
```

```
      DO 611 J=1,NJ
      WRITE (6,23) HMEAN(J)
      IF(IHTAG(J).EQ.0) GO TO 613
      WRITE(6,20)
      GO TO 611
  613 WRITE(6,22) POWER(J),HTOTAL(J),DELTJ(J),TORQUE(J)
  611 CONTINUE
  612 IF (ASKIP)  GO TO 700
C
C     WRITE X AND PRESSURE DISTRIBUTIONS
C
      JJ = 0
      DO 620  J=1, NJ
      IF (IHTAG(J).NE.0)   GO TO 620
      JJ = JJ+1
      IF (MOD(JJ,JMOD).EQ.1)  WRITE (6,57)
      WRITE (6,18) HMEAN(J)
      WRITE (6,19) (X(J,I),PRAT(J,I),P(J,I),UAVRG(J,I),MACH(J,I),
     1 I=1,NN)
  620 CONTINUE
C
C     PLOT ROUTINE
C
  700 KODE = 6
      PP(3) = 0.
      PP(4) = 0.
      DO 701 J=1,NJ
      IF (IHTAG(J).NE.0)  HMEAN(J)=-HMEAN(J)
  701 CONTINUE
  720 IF (TSKIP)       GO TO 730
      IF (SPEED.EQ.0.)    GO TO 730
      CALL ARRNG(HMEAN,POWER,XPLOT,YPLOT,NJ,NP)
      PP(1) = NP
      WRITE (6,34)
      CALL PLOTXY(XPLOT,YPLOT,KODE,PP)
      WRITE (6,43)
  730 IF (ASKIP)       GO TO 750
      DO 741 J=1,NJ
      IF (IHTAG(J).NE.0)   GO TO 741
      WRITE (6,37) HMEAN(J)
      DO 740 I=1,NN
      XPT(I) = X(J,I)
      YPT(I) = PRAT(J,I)
  740 CONTINUE
      CALL ARRNG (XPT,YPT,XPLOT,YPLOT,NN,NP)
      PP(1) = NP
      CALL PLOTXY(XPLOT,YPLOT,KODE,PP)
      WRITE (6,46)
      GO TO 750
  741 CONTINUE
  750 DO 751 J=1,NJ
      IF (IHTAG(J).NE.0)  HMEAN(J)=-HMEAN(J)
  751 CONTINUE
C
C     CONVERT TO INTERNATIONAL UNITS AND PRINT
C
  800 IF (NOUI)  GO TO 100
      UI(21)= RHOREF*517.2026
      UI(22)= RHO1*517.2026
      UI(23) = A*.3048
```

```
      UI(24) = SPEED/60.
      UI(25) = R*5.38095
      UI(26)= L*2.54E-2
      UI(27)= AREA*6.4516E-4
      UI(28)= CAPV*.3048
      WRITE (6,10)
      WRITE (6,54) TITLE
      WRITE (6,50) (UI(I),I=2,12),NN,(UI(I),I=13,15),ASKIP,RSKIP,
     1 TSKIP,(UI(I),I=21,28)
      WRITE (6,13)
      IF (.NOT.RSKIP)   WRITE (6,14)
      WRITE (6,51)
      IF (.NOT.RSKIP)  WRITE (6,56)
      DO 810 J=1,NJ
      UH = HMEAN(J)*2.54E-2
      WRITE (6,23) UH
      IF (IHTAG(J).EQ.0)    GO TO 809
      WRITE (6,20)
      GO TO 810
  809 UM = MDOT(J)*.755987E-2
      UQ = Q(J)*.47194744E-3
      UF = F(J)*4.4482216
      UXC  = XC(J)*2.54E-2
      WRITE (6,15) UM,UQ,MACHMX(J),REP(J),RER(J),KN(J),UF,UXC
      IF(.NOT.RSKIP) WRITE(6,16) XCBAR(J),FBAR(J)
  810 CONTINUE
      IF (TSKIP)  GO TO 812
      WRITE (6,52)
      DO 811 J=1,NJ
      UH = HMEAN(J)*2.54E-2
      WRITE (6,23) UH
      IF(IHTAG(J).NE.0) GO TO 813
      UP = POWER(J)*7.4569987E2
      UHT = HTOTAL(J)*17.597833
      UT =  DELTJ(J)/1.8
      UTRK  = TORQUE(J)*1.3558179
      WRITE(6,22) UP,UHT,UT,UTRK
      GO TO 811
  813 WRITE(6,20)
  811 CONTINUE
  812 IF (ASKIP)  GO TO 100
      JJ = 0
      DO 821 J=1,NJ
      IF (IHTAG(J).NE.0)    GO TO 821
      JJ = JJ+1
      IF (MOD(JJ,JMOD).EQ.1)   WRITE (6,57)
      UH = HMEAN(J)*2.54E-2
      WRITE (6,53) UH
      DO 820 I=1,NN
      UX = X(J,I)*2.54E-2
      UP = P(J,I)*6.8947572E3
      UV= UAVRG(J,I)*.3048
      WRITE (6,19) UX,PRAT(J,I),UP,UV,MACH(J,I)
  820 CONTINUE
  821 CONTINUE
      GO TO 100
C
    1 FORMAT (I3)
    2 FORMAT (6F12.6)
    3 FORMAT (12A6)
```

```
10 FORMAT (1H1,60HCOMPRESSIBLE SEALING DAM WITH ROTATION AND PARALLEL
  1 SURFACES)
11 FORMAT (1H0,12HINPUT DATA -,/,
  1 1H0,6X,7HP2,PSIA,10X,7HP1,PSIA,10X,7HT,DEG F,10X,
  2 20HVISCOSITY,LB-SEC/FT2,10X,16HMOLECULAR WEIGHT, 18X,5HCP/CV,/,
  3 1H ,2G17.5,F13.0,G25.5,G31.5,G28.5,/,1H0,4X,9HR2,INCHES,8X,
  4 9HR1,INCHES,9X,8HL,INCHES,10X,15HRHO,LB-SEC2/FT4,10X,
  5 20HRHO(ROT),LB-SEC2/FT4,10X,17HNO OF GRID POINTS,/,1H ,3G17.5,
  6 G21.5,G27.5,I22,/,1H0,6X,5HN,RPM,11X,8HV,FT/SEC,9X,
  7 15HCP,BTU/LB-DEG R,13X,6HSKIP A,6X,6HSKIP R,6X,6HSKIP T,/,1H ,
  8 2G17.5,G18.5,L19,2L12)
12 FORMAT (1H0,17HBEGIN OUTPUT DATA,/,1H0,7X,
  1 20HRHO(ROT),LB-SEC2/FT4,4X,18HRHO(1),LB-SEC2/FT4,6X,
  2 21HA(SOUND SPEED),FT/SEC,6X,9HSPEED,RPM,/,1H ,2G22.5,G26.5,G23.5,
  3 /,1H0,3X,30HGAS CONSTANT,FT-LB/LB(M)-DEG R,10X,8HL,INCHES,12X,
  4 8HAREA,IN2,12X,8HV,FT/SEC,/,1H ,G24.5,G31.5, 2G20.5)
13 FORMAT (1H0,2X,9HMEAN FILM,4X,6HM(DOT),6X,1HQ,8X,4HMACH,5X,
  1 5HRE(P),6X,5HRE(R),5X,7HKNUDSEN,7X,1HF,9X,2HXC)
14 FORMAT (1H+,100X,2HXC,8X,1HF)
15 FORMAT (1H+,11X,2G11.3,2F9.3,2F10.3,F12.3,G11.3)
16 FORMAT (1H+,93X,2F10.3)
17 FORMAT (1H0,16HMEAN FILM,INCHES,8X,10HPOWER,H.P.,6X,
  1 18HSHEAR HEAT,BTU/MIN,5X,12HDEL(T),DEG F,8X,12HTORQUE,FT-LB)
18 FORMAT (1H0,11HMEAN FILM =,G11.3,2X,6HINCHES,/,1H0,5X,8HX,INCHES,
  1 4X,8HP/P(MIN),7X,5HP,PSI,6X,12HU(AV),FT/SEC,4X,7HMACH NO)
19 FORMAT (1H ,G14.3,4G14.5)
20 FORMAT (1H+,77X,18HANALYSIS NOT VALID)
21 FORMAT (1H0,39HNUMERICAL INTEGRATION IN S IS INCORRECT)
22 FORMAT (1H+, 15X,4G20.5)
23 FORMAT (1H ,G11.3)
24 FORMAT (1H0,26HFOR MEAN FILM THICKENESS =,G15.5,3X,
  1 14HF IS INCORRECT)
25 FORMAT (1H0,26HFOR MEAN FILM THICKENESS =,G15.5,3X,
  1 15HXC IS INCORRECT)
30 FORMAT (2HPT,55HPLOT OF M(DOT) AND Q VS H(MEAN) WHERE Q = 13.083*M
  1(DOT)    )
32 FORMAT (2HPT,23HPLOT OF X(C) VS H(MEAN))
33 FORMAT (2HPT,28HPLOT OF MDOT(BAR) VS H(MEAN))
34 FORMAT (2HPT,24HPLOT OF POWER VS H(MEAN))
37 FORMAT (2HPT,35HPLOT OF P/P(MIN) VS X FOR H(MEAN) =,G15.5)
38 FORMAT (2HPT,25HPLOT OF F(BAR) VS H(MEAN))
40 FORMAT (2HPL,50HXC ON VERTICAL SCALE - H(MEAN) ON HORIZONTAL SCALE
  1 ,/,2HPL,/,2HPL,10X,56HXC IN INCHES - TO CONVERT TO METERS, MULTIP
  2LY BY 2.54E-2  ,/,2HPL,/,2HPL,10X,61HH(MEAN) IN INCHES - TO CONVER
  3T TO METERS, MULTIPLY BY 2.54E-2 )
41 FORMAT (2HPL,54HM(BAR) ON VERTICAL SCALE - H(MEAN) ON HORIZONTAL S
  1CALE,/,2HPL,/,2HPL,10X,23HM(BAR) IS DIMENSIONLESS,/,2HPL,/,2HPL,
  2 10X,61HH(MEAN) IN INCHES - TO CONVERT TO METERS, MULTIPLY BY 2.54
  3E-2)
42 FORMAT (2HPL,54HF(BAR) ON VERTICAL SCALE - H(MEAN) ON HORIZONTAL S
  1CALE,/,2HPL,/,2HPL,10X,23HF(BAR) IS DIMENSIONLESS,/,2HPL,/,2HPL,
  2 10X,61HH(MEAN) IN INCHES - TO CONVERT TO METERS, MULTIPLY BY 2.54
  3E-2)
43 FORMAT (2HPL,53HPOWER ON VERTICAL SCALE - H(MEAN) ON HORIZONTAL SC
  1ALE,/,2HPL,/,2HPL,10X,61HPOWER IN HORSE POWER - TO CONVERT TO WATT
  2S, MULTIPLY BY 745.7,/,2HPL,/,2HPL,10X,61HH(MEAN) IN INCHES - TO C
  3ONVERT TO METERS, MULTIPLY BY 2.54E-2,/,2HPL,/,2HPL,50HFOR SHEAR H
  4EAT IN BTU/MIN, MULTIPLY POWER BY 42.42)
46 FORMAT (2HPL,50HP/P(MIN) ON VERTICAL SCALE - X ON HORIZONTAL SCALE
  1,/,2HPL,/,2HPL,10X,25HP/P(MIN) IS DIMENSIONLESS,/,2HPL,/,2HPL,10X,
```

```
    2 55HX IN INCHES - TO CONVERT TO METERS, MULTIPLY BY 2.54E-2)
 50 FORMAT (1H0,5X,7HP2,N/M2,
    1 9X,7HP1,N/M2,10X,7HT,DEG K,10X,16HVISCOSITY,N-S/M2,10X,
    2 16HMOLECULAR WEIGHT,14X,5HCP/CV,/,1H ,G14.5,G17.5,F14.0,G24.5,
    3 G26.5,G27.5,/,1H0,4X,9HR2,METERS,7X,9HR1,METERS,9X,8HL,METERS,
    4 13X,9HRHO,KG/M3,12X,14HRHO(ROT),KG/M3,10X,
    5 17HNO OF GRID POINTS,/,1H ,G14.5,G17.5,G18.5,G21.5,G22.5,I22,/,
    6 1H0,6X,5HN,RPS,12X,5HV,M/S,9X,13HCP,J/KG-DEG K,
    7 16X,6HSKIP A,6X,6HSKIP R,6X,6HSKIP T,/,1H ,G15.5,G17.5,
    8 G18.5,L20,2L12,/,1H0,17HBEGIN OUTPUT DATA,/,1H0,5X,
    9 14HRHO(ROT),KG/M3,10X,12HRHO(1),KG/M3,10X,
    X 18HA(SOUND SPEED),M/S,6X,9HSPEED,RPS,/,1H ,G17.5,G23.5,G28.5,
    1 G19.5,/,1H0,3X,23HGAS CONSTANT,J/KG-DEG K,10X,8HL,METERS,15X,
    2 7HAREA,M2,14X,5HV,M/S,/,1H ,G20.5,G28.5,G22.5,G20.5)
 51 FORMAT (1H ,4X,6HMETERS,5X,6HKG/SEC,5X,4HSCMS,6X,5H(MAX),25X,
    1 6HNUMBER,5X,7HNEWTONS,4X,6HMETERS)
 52 FORMAT (1H0,16HMEAN FILM,METERS,7X,11HPOWER,WATTS,8X,
    1 16HTOTAL HEAT,WATTS,6X,12HDEL(T),DEG K,8X,10HTORQUE, N-M)
 53 FORMAT (1H0,11HMEAN FILM =,G14.5,2X,6HMETERS,/,1H0,5X,8HX,METERS,
    1 4X,8HP/P(MIN),7X,6HP,N/M2,6X,11HU(AV),M/SEC,5X,7HMACH NO)
 54 FORMAT (1H0,12A6)
 55 FORMAT (1H ,3X,6HINCHES,6X,6HLB/MIN,5X,4HSCFM,6X,5H(MAX),25X,
    1 6HNUMBER,8X,2HLB,6X,6HINCHES)
 56 FORMAT (1H+,99X,3HBAR,7X,3HBAR)
 57 FORMAT (1H1)
C
      END
```

```
$IBFTC PRESR
C
C     PRESSURE FUNCTION
C
      FUNCTION PRESS(X)
      COMMON/INTGRL/PREF,RR1,EA,AA,S
      EXTERNAL ROT
C
      R1 = RR1
      K = 0
      QQ = 0.
      IF (X.NE.0.)    QQ=SIMPS2(R1,0.,X,ROT,K)
      Q = EXPR(-(X+R1)**2)*(AA*(QQ/S)+EA)
      IF (K.NE.0)    WRITE (6,10) X
   10 FORMAT( 1H0,7HFOR X =,G15.5,3X,32HINTEGRATION IN P**2 IS INCORRECT)
      Y = SQRT(Q)
      PRESS = Y
      RETURN
      END
```

```
$IBFTC EXPP
C
C     EXPONENTIAL (ECONST*X)
C
      FUNCTION EXPK(X)
      COMMON/ECON/ECONST
      YY = X
      Y = EXP(ECONST*YY)
      EXPK = Y
      DEBUG YY,ECONST,Y
      RETURN
      END
```

```
$IBFTC EXPX
C
C     EXTERNAL FUNCTION FOR INTEGRAL EXP(E(X+R1)**2)/(X+R1) DX
C
      FUNCTION ROT(R1,X)
      YY = X+R1
      Y = EXPK(YY**2)/YY
      ROT = Y
      RETURN
      END
```

```
$IBFTC FPDX
C
C     EXTERNAL FUNCTION FOR INTEGRAL (P-P(REF)) DX
C
      FUNCTION PX(Y)
      COMMON/INTGRL/PREF,A,B,C,D
      YY=Y
      PX = PRESS(YY)-PREF
      RETURN
      END
```

```
$IBFTC FPXDX
C
C     EXTERNAL FUNCTION FOR INTEGRAL (P-P(REF))X DX
C
      FUNCTION PXX(Y)
      COMMON/INTGRL/PREF,A,B,C,D
      YY=Y
      PXX = (PRESS(YY)-PREF)*YY
      RETURN
      END
```

```
$IBFTC SMPSR1
C
C      NUMERICAL INTEGRATION BY SIMPSONS RULE
C
       FUNCTION SIMPS1(XMIN,XMAX,FUNC1,KER)
       DIMENSION V(200),H(200),A(200),B(200),C(200),P(200),E(200),NE(200)
       EQUIVALENCE (E,NE),(TEST,NTEST)
       T=3.0E-5
       V(1)=XMIN
       H(1)=0.5*(XMAX-XMIN)
       A(1)=FUNC1(XMIN)
       B(1)=FUNC1(XMIN+H(1))
       C(1)=FUNC1(XMAX)
       P(1)=H(1)*(A(1)+4.0*B(1)+C(1))
       E(1)=P(1)
       ANS=P(1)
       N=1
       FRAC=2.0*T
     1 FRAC=0.5*FRAC
     2 TEST=ABS(FRAC*ANS)
       K=N
     3 DO 7 I=1,K
     4 IF (NTEST-IABS(NE(I))) 5,5,7
     5 N = N+1
       V(N)=V(I)+H(I)
       H(N)=0.5*H(I)
       A(N)=B(I)
       B(N)=FUNC1(V(N)+H(N))
       C(N)=C(I)
       P(N)=H(N)*(A(N)+4.0*B(N)+C(N))
       Q=P(I)
       H(I)=H(N)
       B(I)=FUNC1(V(I)+H(I))
       C(I)=A(N)
       P(I)=H(I)*(A(I)+4.0*B(I)+C(I))
       Q=P(I)+P(N)-Q
       ANS=ANS+Q
       E(I)=Q
       E(N)=Q
     6 IF (N-200) 7,13,13
     7 CONTINUE
     8 IF (N-K) 9,9,2
     9 Q = 0.0
    10 DO 11 I=1,N
    11 Q=Q+E(I)
    12 IF (ABS(Q)-T*ABS(ANS)) 14,14,1
    13 KER=KER+1
    14 ANS=0.0
    15 DO 16 I=1,N
    16 ANS=ANS+P(I)
       SIMPS1=(ANS+Q/30.0)/3.0
    17 RETURN
       END
```

```
$IBFTC SMPSR2
C
C      NUMERICAL INTEGRATION BY SIMPSONS RULE
C
       FUNCTION SIMPS2(Y,XMIN,XMAX,FUNC2,KER)
       DIMENSION V(200),H(200),A(200),B(200),C(200),P(200),E(200),NE(200)
       EQUIVALENCE (E,NE),(TEST,NTEST)
       T=3.0E-5
       V(1)=XMIN
       H(1)=0.5*(XMAX-XMIN)
       A(1)=FUNC2(Y,XMIN)
       B(1)=FUNC2(Y,XMIN+H(1))
       C(1)=FUNC2(Y,XMAX)
       P(1)=H(1)*(A(1)+4.0*B(1)+C(1))
       E(1)=P(1)
       ANS=P(1)
       N=1
       FRAC=2.0*T
     1 FRAC=0.5*FRAC
     2 TEST=ABS(FRAC*ANS)
       K=N
     3 DO 7 I=1,K
     4 IF (NTEST-IABS(NE(I))) 5,5,7
     5 N = N+1
       V(N)=V(I)+H(I)
       H(N)=0.5*H(I)
       A(N)=B(I)
       B(N)=FUNC2(Y,V(N)+H(N))
       C(N)=C(I)
       P(N)=H(N)*(A(N)+4.0*B(N)+C(N))
       Q=P(I)
       H(I)=H(N)
       B(I)=FUNC2(Y,V(I)+H(I))
       C(I)=A(N)
       P(I)=H(I)*(A(I)+4.0*B(I)+C(I))
       Q=P(I)+P(N)-Q
       ANS=ANS+Q
       E(I)=Q
       E(N)=Q
     6 IF (N-200) 7,13,13
     7 CONTINUE
     8 IF (N-K) 9,9,2
     9 Q = 0.0
    10 DO 11 I=1,N
    11 Q=Q+E(I)
    12 IF (ABS(Q)-T*ABS(ANS)) 14,14,1
13     KER=KER+2
    14 ANS=0.0
    15 DO 16 I=1,N
    16 ANS=ANS+P(I)
       SIMPS2=(ANS+Q/30.0)/3.0
    17 RETURN
       END
```

```
$IBFTC RRANG
C
C      SUBROUTINE TO ARRANGE ARRAYS TO BE PLOTTED
C
      SUBROUTINE ARRNG (X,Y,XP,YP,N,I)
      DIMENSION X(25),Y(25),XP(25),YP(25)
      I = 1
      DO 100 J=1,N
      IF (X(J).LT.0.)   GO TO 100
      XP(I) = Y(J)
      YP(I) = X(J)
      I = I+1
  100 CONTINUE
      I = I-1
      CALL SORTXY (XP,YP,I)
      I1 = I/2
      DO 101 J=1,I1
      IJ = I-J+1
      T = YP(J)
      YP(J) = YP(IJ)
      YP(IJ) = T
      T = XP(J)
      XP(J) = XP(IJ)
      XP(IJ) = T
  101 CONTINUE
      RETURN
      END
```

APPENDIX C

SAMPLE PROBLEM

An example of the use of the computer program will now be given with the following conditions: Air at 45.0 psia is to be sealed from ambient air at 15.0 psia using a seal operating in the externally pressurized mode. The mean temperature is 100° F. The sealing dam outside diameter is 6.630 inches, inside diameter is 6.530 inches, and the design speed is 2795 rpm.

It is desired to find a design mean film thickness which is large enough so that power dissipation and viscous heating temperature rise are sufficiently low, yet small enough so that the mass leakage is tolerable. From our experience, the best method is to try mean film thickness inputs of 0.1 to 1.0 mil in increments of 0.1 mil. The output desired is the mass and volume flow rates, sealing dam force due to the pressure drop, center of pressure, power loss, and approximate temperature rise due to shearing. A check on the validity of the analysis is made by examining the Mach number, Knudsen number, and rotational and pressure flow Reynolds numbers. Thus the program input will include

Speed of rotation, N, rpm	2796
Molecular weight of gas, m. lbm/(lb-mole)	28.9660
Pressure at inner radius or inlet, P_1, psia	15.0
Pressure at outer radius or exit, P_2, psia	45.0
Absolute or dynamic viscosity, μ, lbf-sec/ft^2	3.06×10^{-7}
Specific heat at constant pressure, C_p, Btu/lbm-$^{\circ}$R	0.24
Mean film thickness (increase in increments of 0.1), h_m, mil	0.1 to 1.0
Temperature, T, $^{\circ}$F	100
Inner radius, R_1, in.	3.265
Outer radius, R_2, in.	3.315
Specific heat ratio, γ	1.4

The data sheet for this sample problem is shown in table III. The sample output, with all possible output options are shown in both English and SI units. Note that the analysis is invalid for film thicknesses greater than 0.5 mil (where the Mach number has exceeded $1/\sqrt{\gamma} = 0.845$). The pressure and velocity distributions, torque, and plots of pressure and power versus mean film thickness are included for a more detailed examination of this problem. This problem ran in approximately 0.1 minute on the Lewis computer.

TABLE III. - INPUT DATA SHEET

TITLE	PROJECT NUMBER	ANALYST	SHEET ___ OF ___
Data for Sample Problem			

STATEMENT NUMBER | CONT | FORTRAN STATEMENT | IDENTIFICATION

```
            SAMPLE PROBLEM

 14

 .0010      .0009       .0008       .0007       .0006       .0005
 .00045     .0004       .00035      .0003       .00025      .0002
 .00015     .0001

 $RINPT L=0., SPEED=2796., CAPV=0., MOLWT=28.966, P1=15., P2=45., T=100.,
 R1=3.265, R2=3.315, RHØRO., RHORF=0., MU=.396E-6, CP=.24, GAMMA=1.4,
 NGRID=10, ASKIP=F, TSKIP=F, RSKIP=F, NOUI=F $
```

NASA-C-836 (REV 9-14-59)

CD-6729

COMPRESSIBLE SEALING DAM WITH ROTATION AND PARALLEL SURFACES

SAMPLE PROBLEM

INPUT DATA -

P2,PSIA	P1,PSIA	T,DEG F	VISCOSITY,LB-SEC/FT2	MOLECULAR WEIGHT	CP/CV
45.0000	15.0000	100.	0.38600E-06	28.9660	1.40000

R2,INCHES	R1,INCHES	L,INCHES	RHO,LB-SEC2/FT4	RHO(ROT),LB-SEC2/FT4	NO OF GRID POINTS
3.31500	3.26500	0	0	0	11

N,RPM	V,FT/SEC	CP,BTU/LB-DEG R	SKIP A	SKIP R	SKIP T
2796.00	0	0.24000	F	F	F

BEGIN OUTPUT DATA

RHO(ROT),LB-SEC2/FT4	RHO(1),LB-SEC2/FT4	A(SOUND SPEED),FT/SEC	SPEED,RPM
0.50321E-02	0.22470E-02	1160.08	2796.00

GAS CONSTANT,FT-LB/LB(M)-DEG R	L,INCHES	AREA,IN2	V,FT/SEC
53.3522	20.6717	1.03358	80.2750

MEAN FILM INCHES	M(DOT) LB/MIN	Q SCFM	MACH (MAX)	RE(P)	RE(R)	KNUDSEN NUMBER	F LB	XC INCHES	XC BAR	F BAR
0.100E-02							ANALYSIS NOT VALID			
0.900E-03							ANALYSIS NOT VALID			
0.800E-03							ANALYSIS NOT VALID			
0.700E-03							ANALYSIS NOT VALID			
0.600E-03							ANALYSIS NOT VALID			
0.500E-03	-0.242	-3.166	0.670	377.006	43.605	0.005	18.125	0.318E-01	0.635	0.585
0.450E-03	-0.176	-2.308	0.543	274.838	39.244	0.006	18.125	0.318E-01	0.635	0.585
0.400E-03	-0.124	-1.621	0.429	193.027	34.884	0.007	18.125	0.318E-01	0.635	0.585
0.350E-03	-0.830E-01	-1.086	0.328	129.313	30.523	0.008	18.125	0.318E-01	0.635	0.585
0.300E-03	-0.523E-01	-0.684	0.241	81.433	26.163	0.009	18.125	0.318E-01	0.635	0.585
0.250E-03	-0.302E-01	-0.396	0.167	47.126	21.802	0.011	18.125	0.318E-01	0.635	0.585
0.200E-03	-0.155E-01	-0.203	0.107	24.128	17.442	0.013	18.125	0.318E-01	0.635	0.585
0.150E-03	-0.653E-02	-0.855E-01	0.060	10.179	13.081	0.018	18.125	0.318E-01	0.635	0.585
0.100E-03	-0.194E-02	-0.253E-01	0.027	3.016	8.721	0.026	18.125	0.318E-01	0.635	0.585

MEAN FILM,INCHES	POWER,H.P.	SHEAR HEAT,BTU/MIN	DEL(T),DEG F	TORQUE,FT-LB
0.100E-02				ANALYSIS NOT VALID
0.900E-03				ANALYSIS NOT VALID
0.800E-03				ANALYSIS NOT VALID
0.700E-03				ANALYSIS NOT VALID
0.600E-03				ANALYSIS NOT VALID
0.500E-03	0.77908E-03	0.33048E-01	0.56909	0.91951E-02
0.450E-03	0.86564E-03	0.36720E-01	0.86739	0.10217E-01
0.400E-03	0.97385E-03	0.41311E-01	1.38939	0.11494E-01
0.350E-03	0.11130E-02	0.47212E-01	2.37023	0.13136E-01
0.300E-03	0.12985E-02	0.55081E-01	4.39115	0.15325E-01
0.250E-03	0.15582E-02	0.66097E-01	9.10548	0.18390E-01
0.200E-03	0.19477E-02	0.82621E-01	22.2302	0.22988E-01
0.150E-03	0.25969E-02	0.11016	70.2583	0.30650E-01
0.100E-03	0.38954E-02	0.16524	355.683	0.45976E-01

MEAN FILM = 0.500E-03 INCHES

X,INCHES	P/P(MIN)	P,PSI	U(AV),FT/SEC	MACH NO
0	1.00000	15.0000	777.157	0.66992
0.500E-02	1.34368	20.1552	578.380	0.49857
0.100E-01	1.61546	24.2319	481.074	0.41469
0.150E-01	1.84736	27.7104	420.685	0.36264
0.200E-01	2.05294	30.7940	378.559	0.32632
0.250E-01	2.23945	33.5917	347.030	0.29914
0.300E-01	2.41133	36.1700	322.294	0.27782
0.350E-01	2.57151	38.5727	302.218	0.26052
0.400E-01	2.72207	40.8310	285.502	0.24611
0.450E-01	2.86451	42.9677	271.305	0.23387
0.500E-01	3.00000	45.0000	259.052	0.22331

MEAN FILM = 0.450E-03 INCHES

X,INCHES	P/P(MIN)	P,PSI	U(AV),FT/SEC	MACH NO
0	1.00000	15.0000	629.497	0.54263
0.500E-02	1.34368	20.1552	468.488	0.40384
0.100E-01	1.61546	24.2319	389.670	0.33590
0.150E-01	1.84736	27.7104	340.755	0.29373
0.200E-01	2.05294	30.7940	306.633	0.26432
0.250E-01	2.23945	33.5917	281.095	0.24231
0.300E-01	2.41133	36.1700	261.058	0.22504
0.350E-01	2.57151	38.5727	244.796	0.21102
0.400E-01	2.72207	40.8310	231.257	0.19935
0.450E-01	2.86451	42.9677	219.757	0.18943
0.500E-01	3.00000	45.0000	209.832	0.18088

MEAN FILM = 0.400E-03 INCHES

X,INCHES	P/P(MIN)	P,PSI	U(AV),FT/SEC	MACH NO
0	1.00000	15.0000	497.381	0.42875
0.500E-02	1.34368	20.1552	370.163	0.31909
0.100E-01	1.61546	24.2319	307.888	0.26540
0.150E-01	1.84736	27.7104	269.239	0.23209
0.200E-01	2.05294	30.7940	242.278	0.20885
0.250E-01	2.23945	33.5917	222.099	0.19145
0.300E-01	2.41133	36.1700	206.268	0.17781
0.350E-01	2.57151	38.5727	193.419	0.16673
0.400E-01	2.72207	40.8310	182.722	0.15751
0.450E-01	2.86451	42.9677	173.635	0.14968
0.500E-01	3.00000	45.0000	165.794	0.14292

MEAN FILM = 0.350E-03 INCHES

X, INCHES	P/P(MIN)	P,PSI	U(AV),FT/SEC	MACH NO
0	1.00000	15.0000	380.807	0.32826
0.500E-02	1.34368	20.1552	283.406	0.24430
0.100E-01	1.61546	24.2319	235.726	0.20320
0.150E-01	1.84736	27.7104	206.136	0.17769
0.200E-01	2.05294	30.7940	185.494	0.15990
0.250E-01	2.23945	33.5917	170.045	0.14658
0.300E-01	2.41133	36.1700	157.924	0.13613
0.350E-01	2.57151	38.5727	148.087	0.12765
0.400E-01	2.72207	40.8310	139.896	0.12059
0.450E-01	2.86451	42.9677	132.940	0.11460
0.500E-01	3.00000	45.0000	126.936	0.10942

MEAN FILM = 0.300E-03 INCHES

X, INCHES	P/P(MIN)	P,PSI	U(AV),FT/SEC	MACH NO
0	1.00000	15.0000	279.777	0.24117
0.500E-02	1.34368	20.1552	208.217	0.17949
0.100E-01	1.61546	24.2319	173.187	0.14929
0.150E-01	1.84736	27.7104	151.447	0.13055
0.200E-01	2.05294	30.7940	136.281	0.11748
0.250E-01	2.23945	33.5917	124.931	0.10769
0.300E-01	2.41133	36.1700	116.026	0.10002
0.350E-01	2.57151	38.5727	108.798	0.93785E-01
0.400E-01	2.72207	40.8310	102.781	0.88598E-01
0.450E-01	2.86451	42.9677	97.6699	0.84193E-01
0.500E-01	3.00000	45.0000	93.2588	0.80390E-01

MEAN FILM = 0.250E-03 INCHES

X, INCHES	P/P(MIN)	P,PSI	U(AV),FT/SEC	MACH NO
0	1.00000	15.0000	194.289	0.16748
0.500E-02	1.34368	20.1552	144.595	0.12464
0.100E-01	1.61546	24.2319	120.269	0.10367
0.150E-01	1.84736	27.7104	105.171	0.90659E-01
0.200E-01	2.05294	30.7940	94.6397	0.81581E-01
0.250E-01	2.23945	33.5917	86.7576	0.74786E-01
0.300E-01	2.41133	36.1700	80.5735	0.69455E-01
0.350E-01	2.57151	38.5727	75.5544	0.65129E-01
0.400E-01	2.72207	40.8310	71.3756	0.61527E-01
0.450E-01	2.86451	42.9677	67.8263	0.58467E-01
0.500E-01	3.00000	45.0000	64.7631	0.55827E-01

MEAN FILM = 0.200E-03 INCHES

X,INCHES	P/P(MIN)	P,PSI	U(AV),FT/SEC	MACH NO
0	1.00000	15.0000	124.345	0.10719
0.500E-02	1.34368	20.1552	92.5409	0.79771E-01
0.100E-01	1.61546	24.2319	76.9719	0.66351E-01
0.150E-01	1.84736	27.7104	67.3096	0.58022E-01
0.200E-01	2.05294	30.7940	60.5694	0.52212E-01
0.250E-01	2.23945	33.5917	55.5249	0.47863E-01
0.300E-01	2.41133	36.1700	51.5670	0.44451E-01
0.350E-01	2.57151	38.5727	48.3548	0.41682E-01
0.400E-01	2.72207	40.8310	45.6804	0.39377E-01
0.450E-01	2.86451	42.9677	43.4088	0.37419E-01
0.500E-01	3.00000	45.0000	41.4484	0.35729E-01

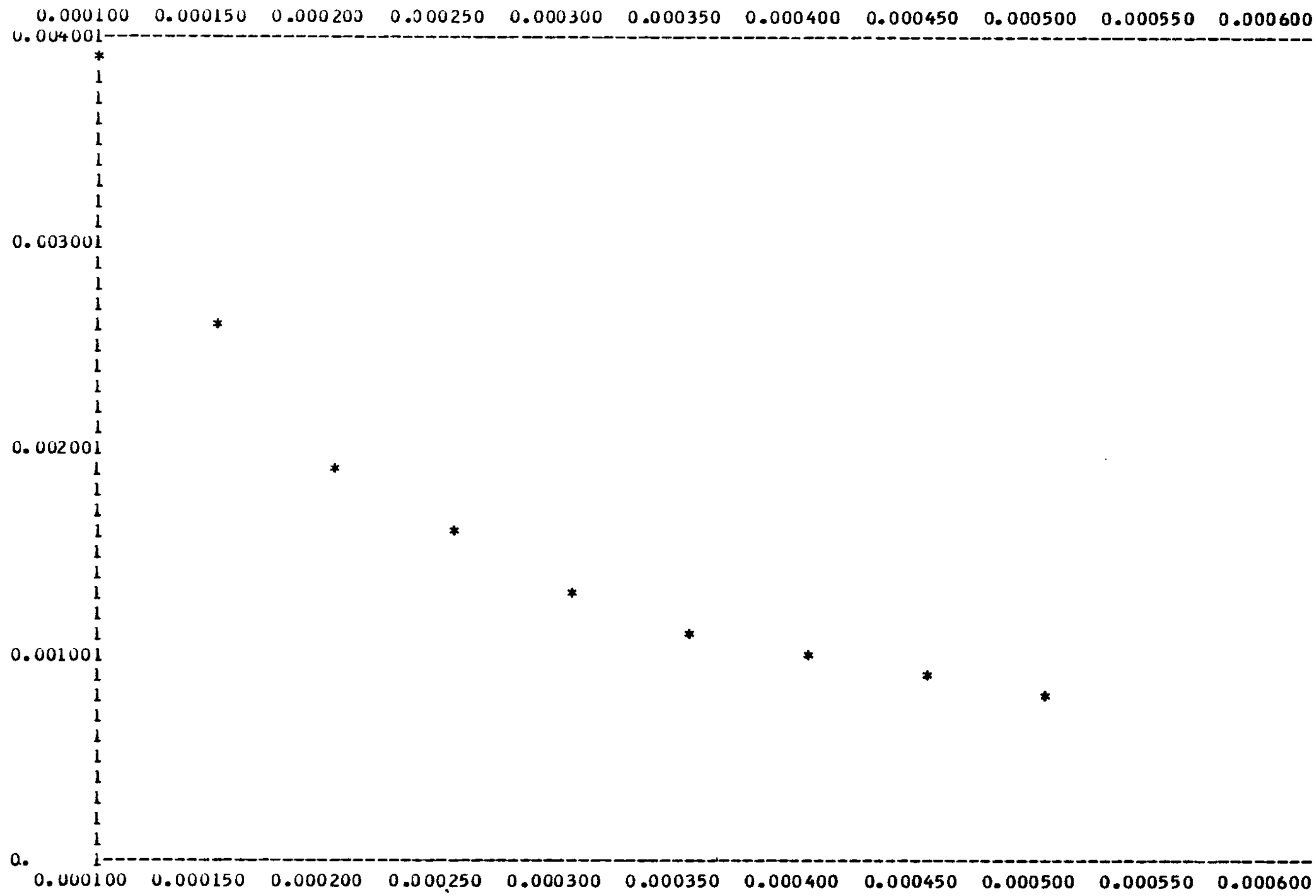
MEAN FILM = 0.150E-03 INCHES

X,INCHES	P/P(MIN)	P,PSI	U(AV),FT/SEC	MACH NO
0	1.00000	15.0000	69.9441	0.60293E-01
0.500E-02	1.34368	20.1552	52.0542	0.44871E-01
0.100E-01	1.61546	24.2319	43.2967	0.37322E-01
0.150E-01	1.84736	27.7104	37.8617	0.32637E-01
0.200E-01	2.05294	30.7940	34.0703	0.29369E-01
0.250E-01	2.23945	33.5917	31.2327	0.26923E-01
0.300E-01	2.41133	36.1700	29.0064	0.25004E-01
0.350E-01	2.57151	38.5727	27.1996	0.23446E-01
0.400E-01	2.72207	40.8310	25.6952	0.22150E-01
0.450E-01	2.86451	42.9677	24.4175	0.21048E-01
0.500E-01	3.00000	45.0000	23.3147	0.20098E-01

MEAN FILM = 0.100E-03 INCHES

X,INCHES	P/P(MIN)	P,PSI	U(AV),FT/SEC	MACH NO
0	1.00000	15.0000	31.0863	0.26797E-01
0.500E-02	1.34368	20.1552	23.1352	0.19943E-01
0.100E-01	1.61546	24.2319	19.2430	0.16588E-01
0.150E-01	1.84736	27.7104	16.8274	0.14505E-01
0.200E-01	2.05294	30.7940	15.1424	0.13053E-01
0.250E-01	2.23945	33.5917	13.8812	0.11966E-01
0.300E-01	2.41133	36.1700	12.8918	0.11113E-01
0.350E-01	2.57151	38.5727	12.0887	0.10421E-01
0.400E-01	2.72207	40.8310	11.4201	0.98443E-02
0.450E-01	2.86451	42.9677	10.8522	0.93547E-02
0.500E-01	3.00000	45.0000	10.3621	0.89322E-02

PLOT OF POWER VS H(MEAN)



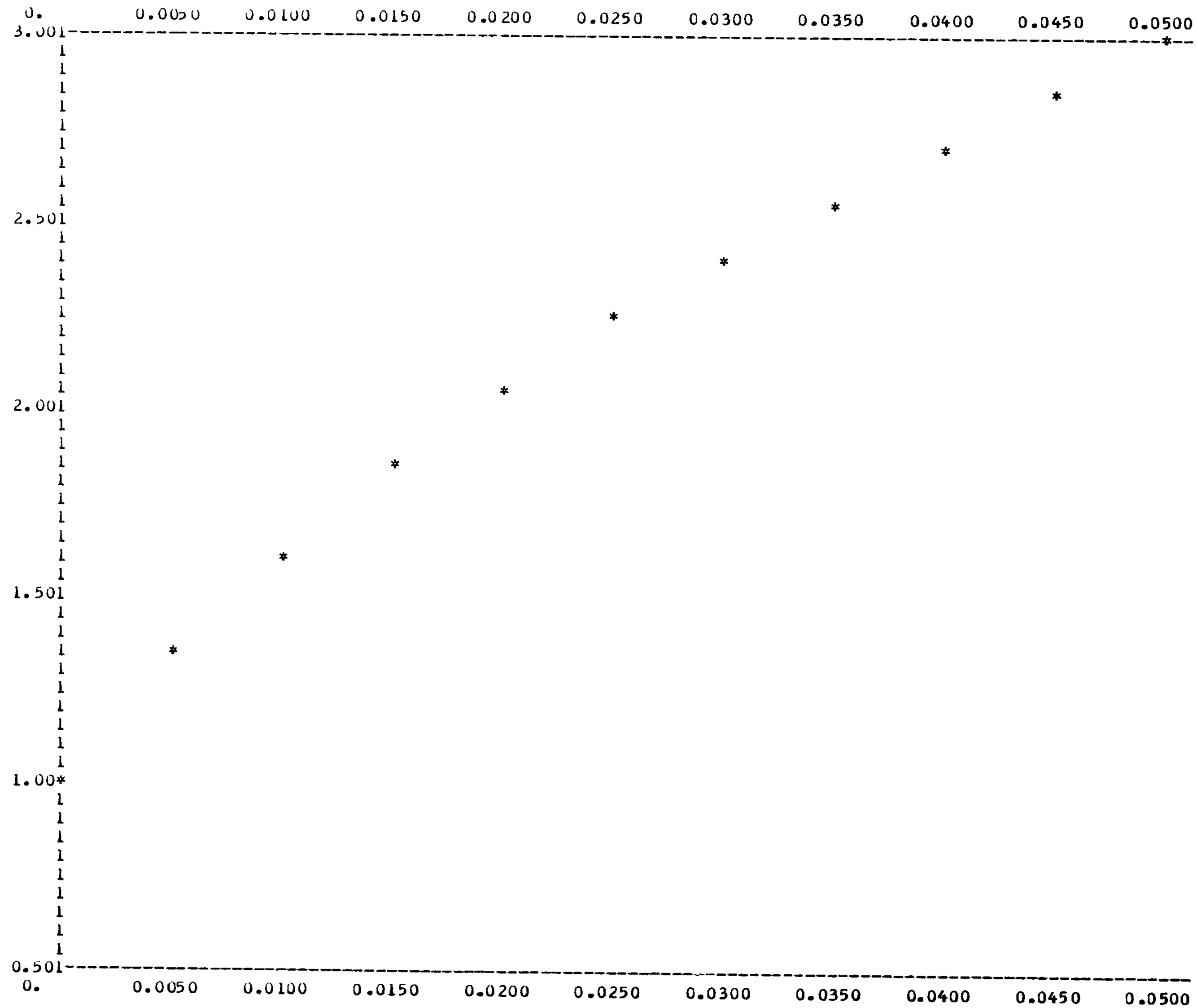
POWER ON VERTICAL SCALE - H(MEAN) ON HORIZONTAL SCALE

POWER IN HORSE POWER - TO CONVERT TO WATTS, MULTIPLY BY 745.7

H(MEAN) IN INCHES - TO CONVERT TO METERS, MULTIPLY BY 2.54E-2

FOR SHEAR HEAT IN BTU/MIN, MULTIPLY POWER BY 42.42

PLOT OF P/P(MIN) VS X FOR H(MEAN) = 0.50000E-03



P/P(MIN) ON VERTICAL SCALE - X ON HORIZONTAL SCALE

P/P(MIN) IS DIMENSIONLESS

X IN INCHES - TO CONVERT TO METERS, MULTIPLY BY 2.54E-2

COMPRESSIBLE SEALING DAM WITH ROTATION AND PARALLEL SURFACES

SAMPLE PROBLEM

P2,N/M2	P1,N/M2	T,DEG K	VISCOSITY,N-S/M2	MOLECULAR WEIGHT	CP/CV
0.31026E 06	0.10342E 06	311.	0.18482E-04	28.9660	1.40000

R2,METERS	R1,METERS	L,METERS	RHO,KG/M3	RHO(ROT),KG/M3	NO OF GRID POINTS
0.84201E-01	0.82931E-01	0	0	0	11

N,RPS	V,M/S	CP,J/KG-DEG K	SKIP A	SKIP R	SKIP T
46.6000	0	1004.78	F	F	F

BEGIN OUTPUT DATA

RHO(ROT),KG/M3	RHO(1),KG/M3	A(SOUND SPEED),M/S	SPEED,RPS
2.60262	1.16217	353.591	46.6000

GAS CONSTANT,J/KG-DEG K	L,METERS	AREA,M2	V,M/S
287.086	0.52506	0.66683E-03	24.4678

MEAN FILM METERS	M(OUT) KG/SEC	Q SCMS	MACH (MAX)	RE(P)	RE(R)	KNUDSEN NUMBER	F NEWTONS	XC METERS	XC BAR	F BAR
0.254E-04							ANALYSIS NOT VALID			
0.229E-04							ANALYSIS NOT VALID			
0.203E-04							ANALYSIS NOT VALID			
0.178E-04							ANALYSIS NOT VALID			
0.152E-04							ANALYSIS NOT VALID			
0.127E-04	-0.183E-02	-0.149E-02	0.670	377.006	43.605	0.005	80.623	0.807E-03	0.635	0.585
0.114E-04	-0.133E-02	-0.109E-02	0.543	274.838	39.244	0.006	80.623	0.807E-03	0.635	0.585
0.102E-04	-0.937E-03	-0.765E-03	0.429	193.027	34.884	0.007	80.623	0.807E-03	0.635	0.585
0.889E-05	-0.627E-03	-0.512E-03	0.328	129.313	30.523	0.008	80.623	0.807E-03	0.635	0.585
0.762E-05	-0.395E-03	-0.323E-03	0.241	81.433	26.163	0.009	80.623	0.807E-03	0.635	0.585
0.635E-05	-0.229E-03	-0.187E-03	0.167	47.126	21.802	0.011	80.623	0.807E-03	0.635	0.585
0.508E-05	-0.117E-03	-0.956E-04	0.107	24.128	17.442	0.013	80.623	0.807E-03	0.635	0.585
0.381E-05	-0.494E-04	-0.403E-04	0.060	10.179	13.081	0.018	80.623	0.807E-03	0.635	0.585
0.254E-05	-0.146E-04	-0.120E-04	0.027	3.016	8.721	0.026	80.623	0.807E-03	0.635	0.585

MEAN FILM,METERS	POWER,WATTS	TOTAL HEAT,WATTS	DEL(T),DEG K	TORQUE,N-M
0.254E-04				ANALYSIS NOT VALID
0.229E-04				ANALYSIS NOT VALID
0.203E-04				ANALYSIS NOT VALID
0.178E-04				ANALYSIS NOT VALID
0.152E-04				ANALYSIS NOT VALID
0.127E-04	0.58096	0.58158	0.31616	0.12467E-01
0.114E-04	0.64551	0.64620	0.48188	0.13852E-01
0.102E-04	0.72620	0.72698	0.77188	0.15584E-01
0.889E-05	0.82994	0.83083	1.31680	0.17810E-01
0.762E-05	0.96826	0.96930	2.43953	0.20778E-01
0.635E-05	1.16191	1.16316	5.05860	0.24934E-01
0.508E-05	1.45239	1.45395	12.3501	0.31167E-01
0.381E-05	1.93652	1.93860	39.0324	0.41556E-01
0.254E-05	2.90479	2.90790	197.602	0.62334E-01

MEAN FILM = 0.12700E-04 METERS

X,METERS	P/P(MIN)	P,N/M2	U(AV),M/SEC	MACH NO
0	1.00000	0.10342E 06	236.877	0.66992
0.127E-03	1.34368	0.13897E 06	176.290	0.49857
0.254E-03	1.61546	0.16707E 06	146.631	0.41469
0.381E-03	1.84736	0.19106E 06	128.225	0.36264
0.508E-03	2.05294	0.21232E 06	115.385	0.32632
0.635E-03	2.23945	0.23161E 06	105.775	0.29914
0.762E-03	2.41133	0.24938E 06	98.2352	0.27782
0.889E-03	2.57151	0.26595E 06	92.1159	0.26052
0.102E-02	2.72207	0.28152E 06	87.0211	0.24611
0.114E-02	2.86451	0.29625E 06	82.6938	0.23387
0.127E-02	3.00000	0.31026E 06	78.9592	0.22331

MEAN FILM = 0.11430E-04 METERS

X,METERS	P/P(MIN)	P,N/M2	U(AV),M/SEC	MACH NO
0	1.00000	0.10342E 06	191.871	0.54263
0.127E-03	1.34368	0.13897E 06	142.795	0.40384
0.254E-03	1.61546	0.16707E 06	118.771	0.33590
0.381E-03	1.84736	0.19106E 06	103.862	0.29373
0.508E-03	2.05294	0.21232E 06	93.4616	0.26432
0.635E-03	2.23945	0.23161E 06	85.6776	0.24231
0.762E-03	2.41133	0.24938E 06	79.5705	0.22504
0.889E-03	2.57151	0.26595E 06	74.6139	0.21102
0.102E-02	2.72207	0.28152E 06	70.4871	0.19935
0.114E-02	2.86451	0.29625E 06	66.9820	0.18943
0.127E-02	3.00000	0.31026E 06	63.9569	0.18088

MEAN FILM = 0.10160E-04 METERS

X,METERS	P/P(MIN)	P,N/M2	U(AV),M/SEC	MACH NO
0	1.00000	0.10342E 06	151.602	0.42875
0.127E-03	1.34368	0.13897E 06	112.826	0.31909
0.254E-03	1.61546	0.16707E 06	93.8441	0.26540
0.381E-03	1.84736	0.19106E 06	82.0639	0.23209
0.508E-03	2.05294	0.21232E 06	73.8462	0.20885
0.635E-03	2.23945	0.23161E 06	67.6959	0.19145
0.762E-03	2.41133	0.24938E 06	62.8705	0.17781
0.889E-03	2.57151	0.26595E 06	58.9542	0.16673
0.102E-02	2.72207	0.28152E 06	55.6935	0.15751
0.114E-02	2.86451	0.29625E 06	52.9241	0.14968
0.127E-02	3.00000	0.31026E 06	50.5339	0.14292

MEAN FILM = 0.88900E-05 METERS

X,METERS	P/P(MIN)	P,N/M2	U(AV),M/SEC	MACH NO
0	1.00000	0.10342E 06	116.070	0.32826
0.127E-03	1.34368	0.13897E 06	86.3823	0.24430
0.254E-03	1.61546	0.16707E 06	71.8494	0.20320
0.381E-03	1.84736	0.19106E 06	62.8302	0.17769
0.508E-03	2.05294	0.21232E 06	56.5385	0.15990
0.635E-03	2.23945	0.23161E 06	51.8297	0.14658
0.762E-03	2.41133	0.24938E 06	48.1352	0.13613
0.889E-03	2.57151	0.26595E 06	45.1368	0.12765
0.102E-02	2.72207	0.28152E 06	42.6404	0.12059
0.114E-02	2.86451	0.29625E 06	40.5200	0.11460
0.127E-02	3.00000	0.31026E 06	38.6900	0.10942

MEAN FILM = 0.76200E-05 METERS

X,METERS	P/P(MIN)	P,N/M2	U(AV),M/SEC	MACH NO
0	1.00000	0.10342E 06	85.2759	0.24117
0.127E-03	1.34368	0.13897E 06	63.4645	0.17949
0.254E-03	1.61546	0.16707E 06	52.7873	0.14929
0.381E-03	1.84736	0.19106E 06	46.1609	0.13055
0.508E-03	2.05294	0.21232E 06	41.5385	0.11748
0.635E-03	2.23945	0.23161E 06	38.0789	0.10769
0.762E-03	2.41133	0.24938E 06	35.3647	0.10002
0.889E-03	2.57151	0.26595E 06	33.1617	0.93785E-01
0.102E-02	2.72207	0.28152E 06	31.3276	0.88598E-01
0.114E-02	2.86451	0.29625E 06	29.7698	0.84193E-01
0.127E-02	3.00000	0.31026E 06	28.4253	0.80390E-01

MEAN FILM = 0.63500E-05 METERS

X,METERS	P/P(MIN)	P,N/M2	U(AV),M/SEC	MACH NO
0	1.00000	0.10342E 06	59.2194	0.16748
0.127E-03	1.34368	0.13897E 06	44.0726	0.12464
0.254E-03	1.61546	0.16707E 06	36.6579	0.10367
0.381E-03	1.84736	0.19106E 06	32.0562	0.90659E-01
0.508E-03	2.05294	0.21232E 06	28.8462	0.81581E-01
0.635E-03	2.23945	0.23161E 06	26.4437	0.74786E-01
0.762E-03	2.41133	0.24938E 06	24.5588	0.69455E-01
0.889E-03	2.57151	0.26595E 06	23.0290	0.65129E-01
0.102E-02	2.72207	0.28152E 06	21.7553	0.61527E-01
0.114E-02	2.86451	0.29625E 06	20.6735	0.58467E-01
0.127E-02	3.00000	0.31026E 06	19.7398	0.55827E-01

MEAN FILM = 0.50800E-05 METERS

X,METERS	P/P(MIN)	P,N/M2	U(AV),M/SEC	MACH NO
0	1.00000	0.10342E 06	37.9004	0.10719
0.127E-03	1.34368	0.13897E 06	28.2065	0.79771E-01
0.254E-03	1.61546	0.16707E 06	23.4510	0.66351E-01
0.381E-03	1.84736	0.19106E 06	20.5160	0.58022E-01
0.508E-03	2.05294	0.21232E 06	18.4016	0.52212E-01
0.635E-03	2.23945	0.23161E 06	16.9240	0.47863E-01
0.762E-03	2.41133	0.24938E 06	15.7175	0.44451E-01
0.889E-03	2.57151	0.26595E 06	14.7385	0.41682E-01
0.102E-02	2.72207	0.28152E 06	13.9234	0.39377E-01
0.114E-02	2.86451	0.29625E 06	13.2310	0.37419E-01
0.127E-02	3.00000	0.31026E 06	12.6335	0.35729E-01

MEAN FILM = 0.38100E-05 METERS

X,METERS	P/P(MIN)	P,N/M2	U(AV),M/SEC	MACH NO
0	1.00000	0.10342E 06	21.3190	0.60293E-01
0.127E-03	1.34368	0.13897E 06	15.8661	0.44871E-01
0.254E-03	1.61546	0.16707E 06	13.1968	0.37322E-01
0.381E-03	1.84736	0.19106E 06	11.5402	0.32637E-01
0.508E-03	2.05294	0.21232E 06	10.3846	0.29369E-01
0.635E-03	2.23945	0.23161E 06	9.51974	0.26923E-01
0.762E-03	2.41133	0.24938E 06	8.84117	0.25004E-01
0.889E-03	2.57151	0.26595E 06	8.29043	0.23446E-01
0.102E-02	2.72207	0.28152E 06	7.83190	0.22150E-01
0.114E-02	2.86451	0.29625E 06	7.44245	0.21048E-01
0.127E-02	3.00000	0.31026E 06	7.10632	0.20098E-01

MEAN FILM = 0.25400E-05 METERS

X,METERS	P/P(MIN)	P,N/M2	U(AV),M/SEC	MACH NO
0	1.00000	0.10342E 06	9.47510	0.26797E-01
0.127E-03	1.34368	0.13897E 06	7.05161	0.19943E-01
0.254E-03	1.61546	0.16707E 06	5.86526	0.16588E-01
0.381E-03	1.84736	0.19106E 06	5.12899	0.14505E-01
0.508E-03	2.05294	0.21232E 06	4.61539	0.13053E-01
0.635E-03	2.23945	0.23161E 06	4.23099	0.11966E-01
0.762E-03	2.41133	0.24938E 06	3.92941	0.11113E-01
0.889E-03	2.57151	0.26595E 06	3.68464	0.10421E-01
0.102E-02	2.72207	0.28152E 06	3.48085	0.98443E-02
0.114E-02	2.86451	0.29625E 06	3.30775	0.93547E-02
0.127E-02	3.00000	0.31026E 06	3.15837	0.89322E-02

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